

Fermi GBM as a Transient Monitor

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Fermi GBM PI

NASA/MSFC

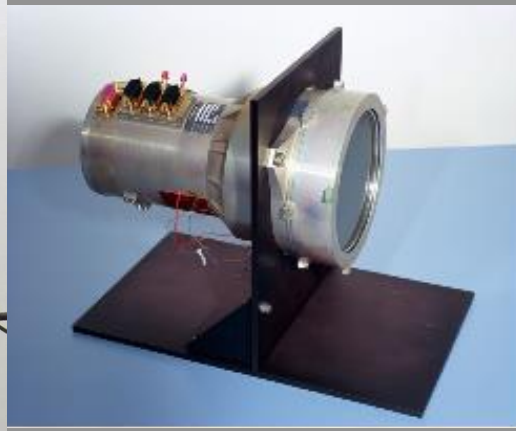
Outline

- GBM Instrument
- Brief transients (milliseconds to minutes)
 - On-board triggers and ground searches
 - Science of EM counterparts to GWs
 - GBM X-ray burst detections
- Long transients & variable sources (hours to years)
 - Earth occultation and accreting pulsar monitoring
 - Observational results
- Conclusions/Future work

Fermi Gamma-ray Burst Monitor (GBM)



NaI



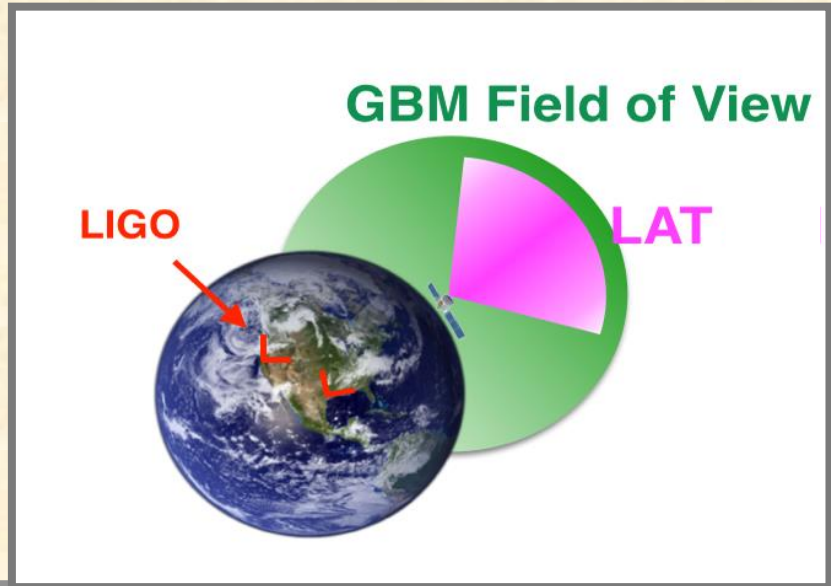
BGO



- GBM detectors are scintillating crystals with attached photomultipliers
- NaI: 8 – 1000 keV
- BGO: 200 keV – 40 MeV

Meegan et al 2009, Apj, 702, 791

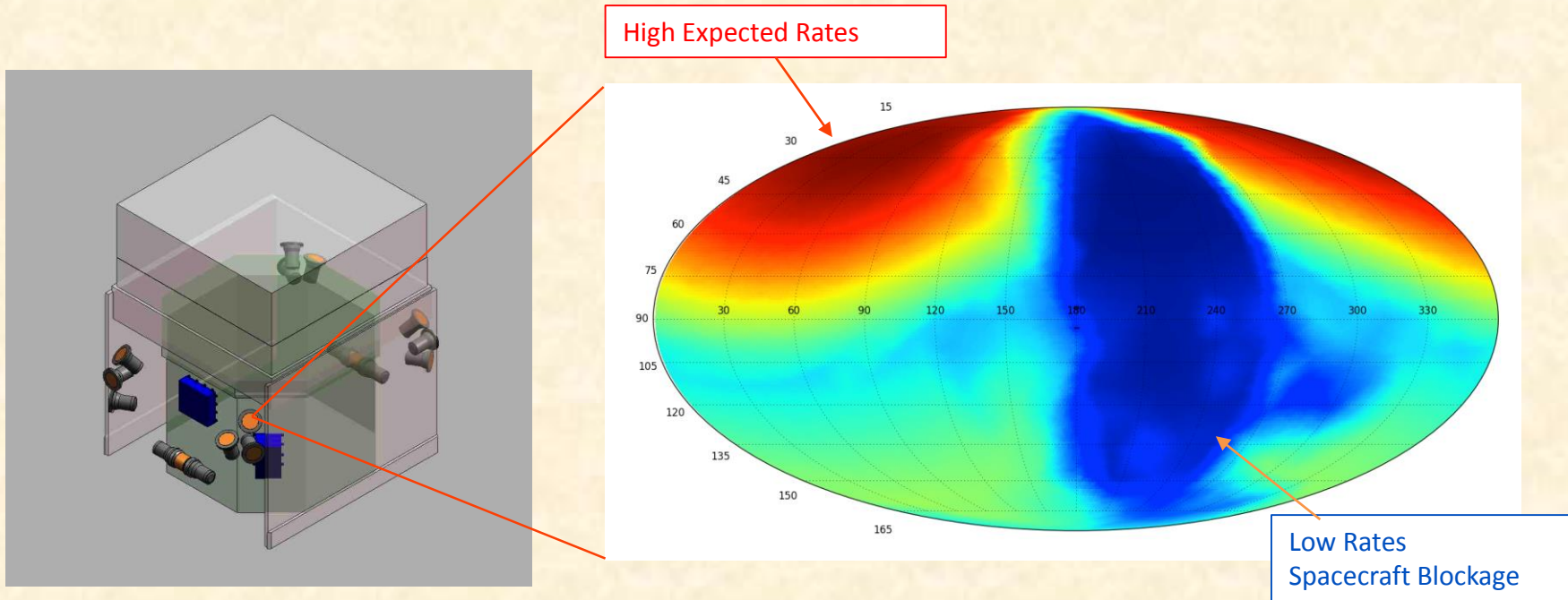
Fermi Gamma-ray Burst Monitor (GBM)



Fermi GBM provides gamma-ray context observations in the Multi-Messenger Era:

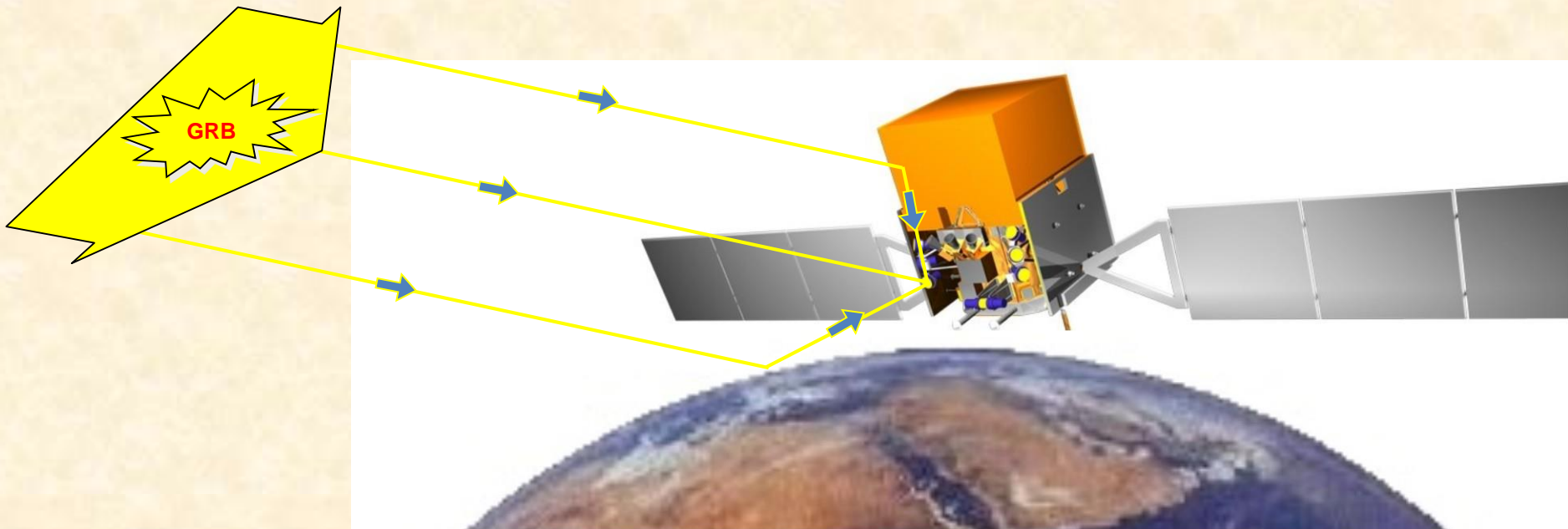
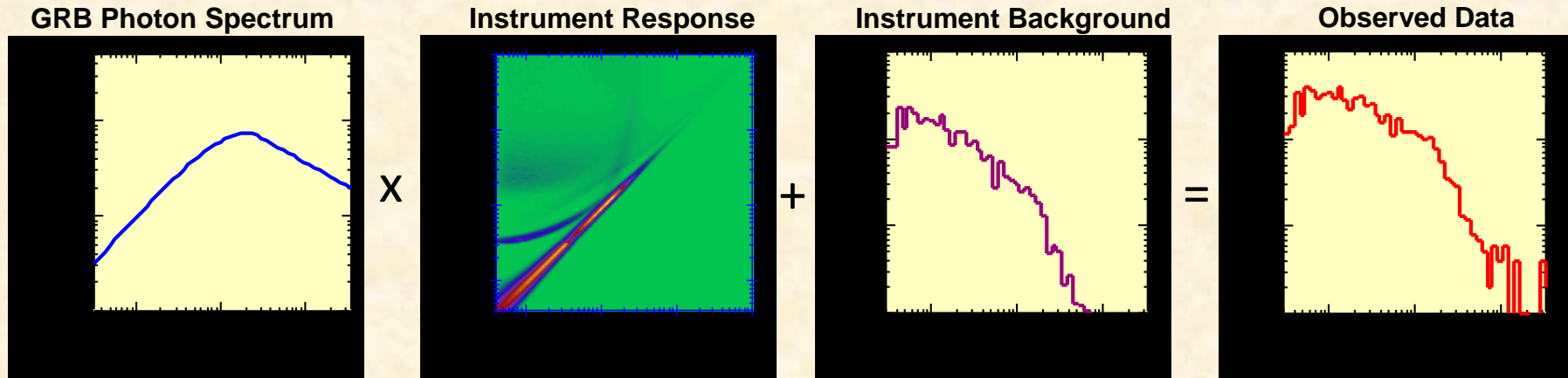
- 87% uptime (off due to SAA),
- Views 69% of sky (Earth blockage),
- Views a particular point on the sky 60% of the time, on average.

GBM Localization Method



- Localization is performed by comparing the relative observed rates from the GRB in each detector to the expected rates on a 1 degree grid
- This requires an assumption of the spectrum, and the sky grid limits to a statistical minimum uncertainty of 1 degree radius

GBM Detector / Instrument Response



GBM Data

Data Type	Time Resolution	Energy Resolution
TRIGDAT	1024/256/64 ms	8 channels
CTIME	256/64 ms	8 channels
CSPEC	4096/1024 ms	128 channels
TTE	2 s	128 channels
CTTE (New!)	2 s	8 channels

- TRIGDAT: used primarily for localization & quick look (triggers only)
- CTIME: temporal analysis
- CPSEC: spectral analysis
- Initially TTE was available ~30s pre-trigger - ~300 s post-trigger
- Continuous TTE (CTTE) implemented on November 26, 2012

Brief Transients

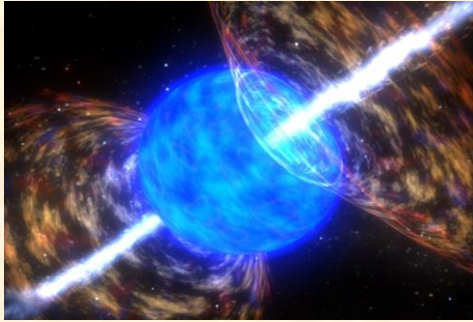
(milliseconds to minutes)

GBM On-Board Triggering

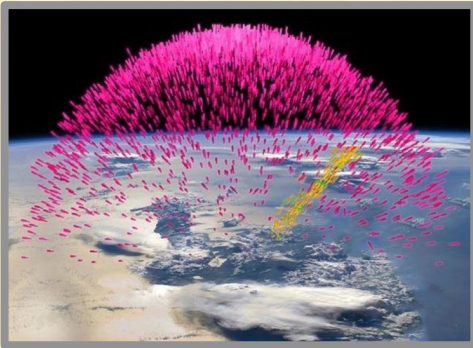
- GBM triggers when 2 or more detectors exceed background by n sigma over timescale t in energy band e .
- 70 algorithms operating simultaneously.
 - $4.5 \leq n \leq 7.5$
 - $16 \text{ ms} \leq t \leq 8.096 \text{ s}$
 - e = one of 25 - 50 keV, 50 - 300 keV, 100 - 300 keV, > 300 keV

⇒ What does GBM trigger on?

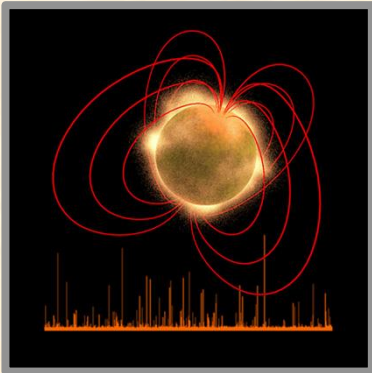
GBM Triggers (2008-2017)



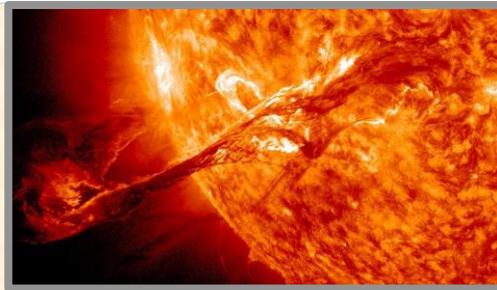
2051 GRBs



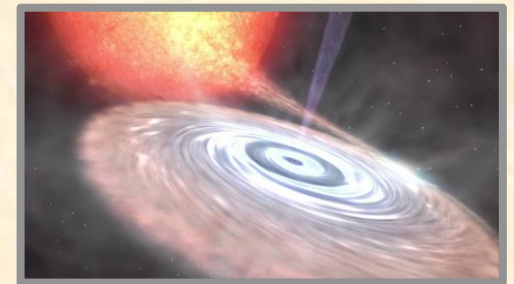
748 TGFs



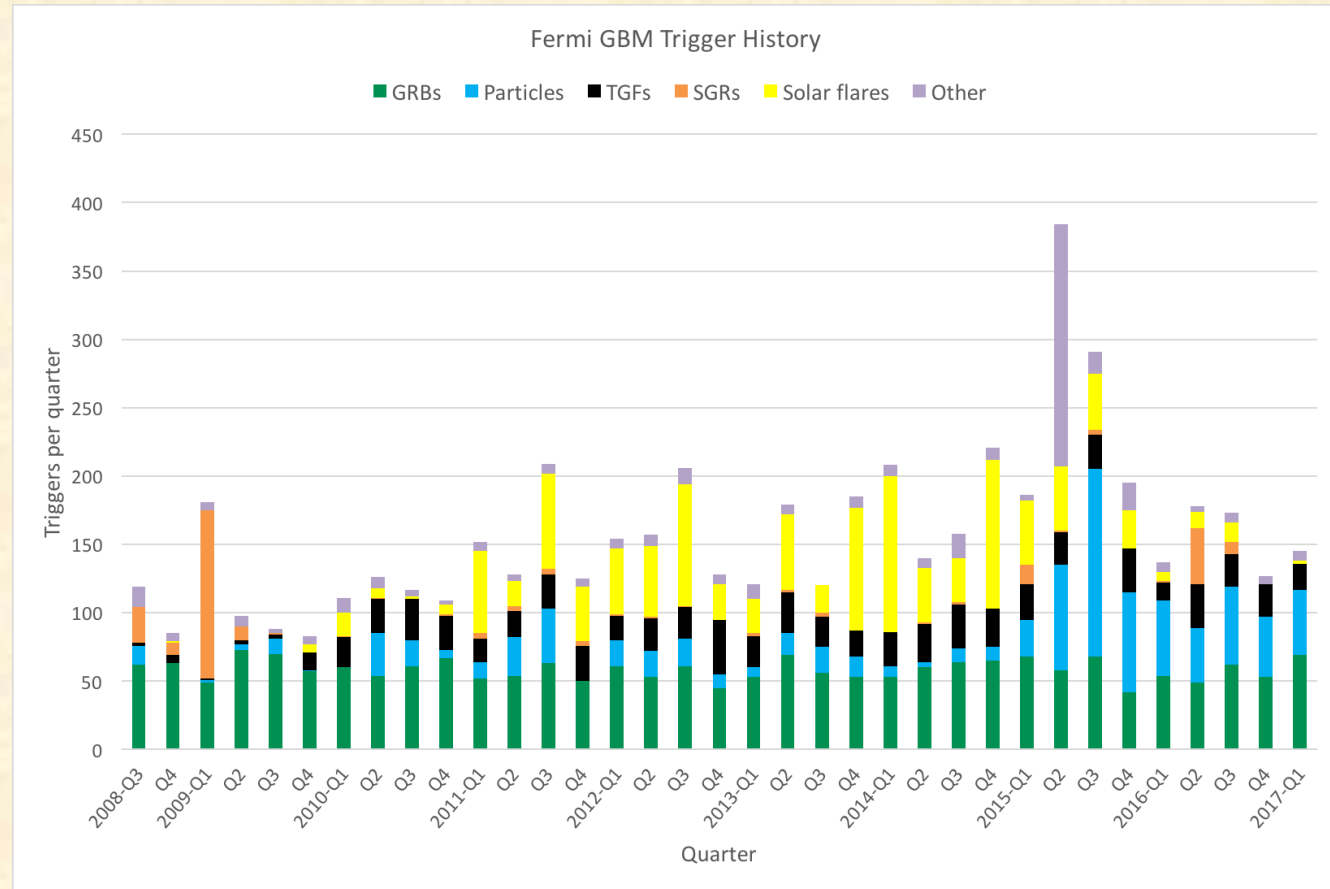
270 SGR bursts



1126 Solar Flares

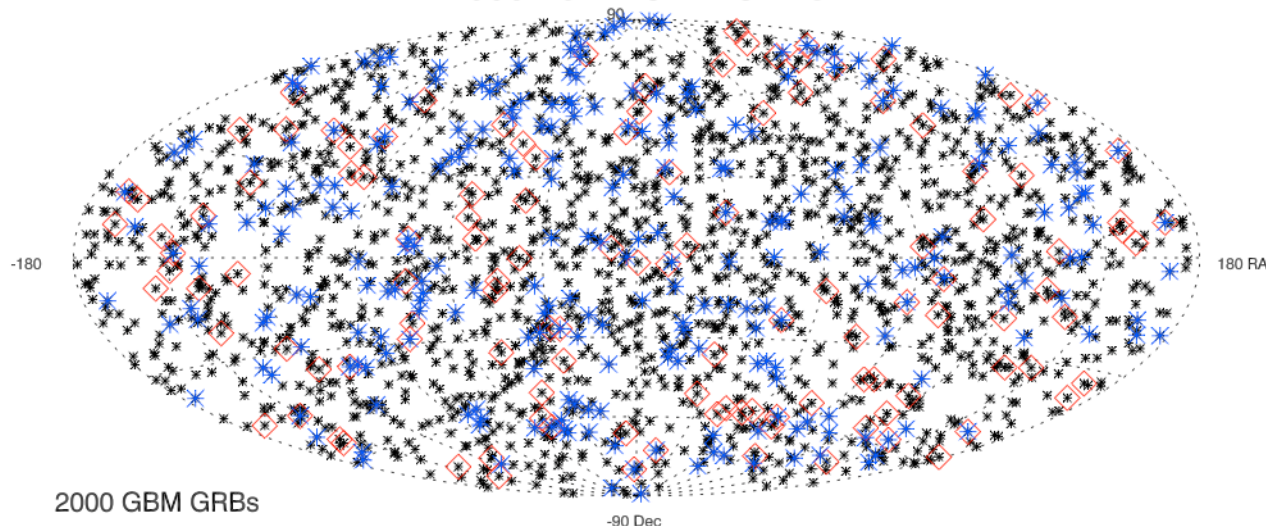


446 Other, 883 particles



GBM Triggered GRBs

2000 Fermi GBM GRBs



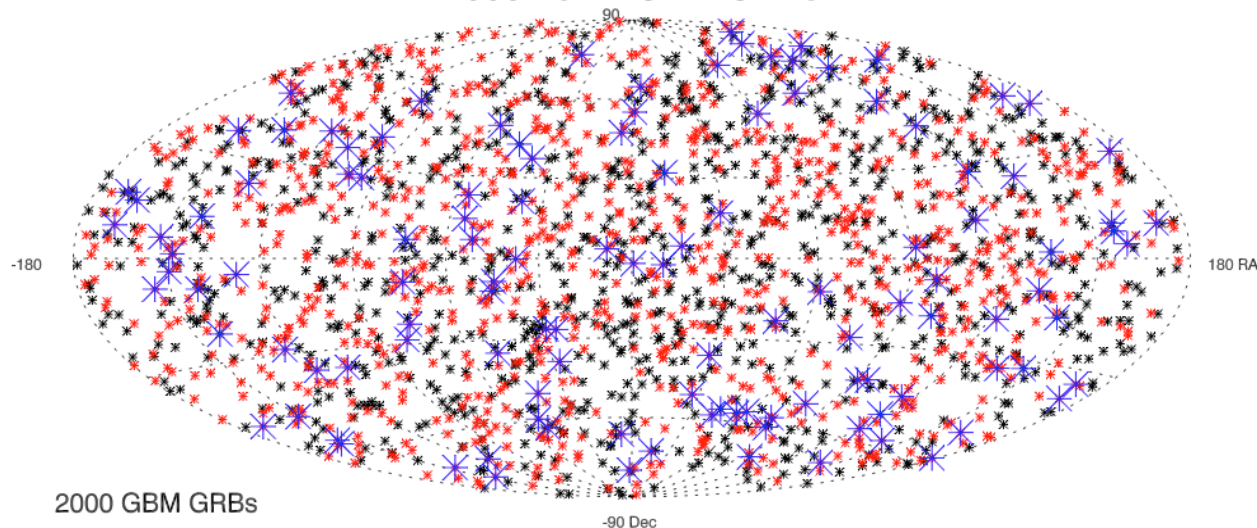
13% Also seen by Swift
6% Also seen with LAT

2000 GBM GRBs

266 Swift GRBs

121 LAT GRBs

2000 Fermi GBM GRBs



2000 GBM GRBs

121 LAT GRBs

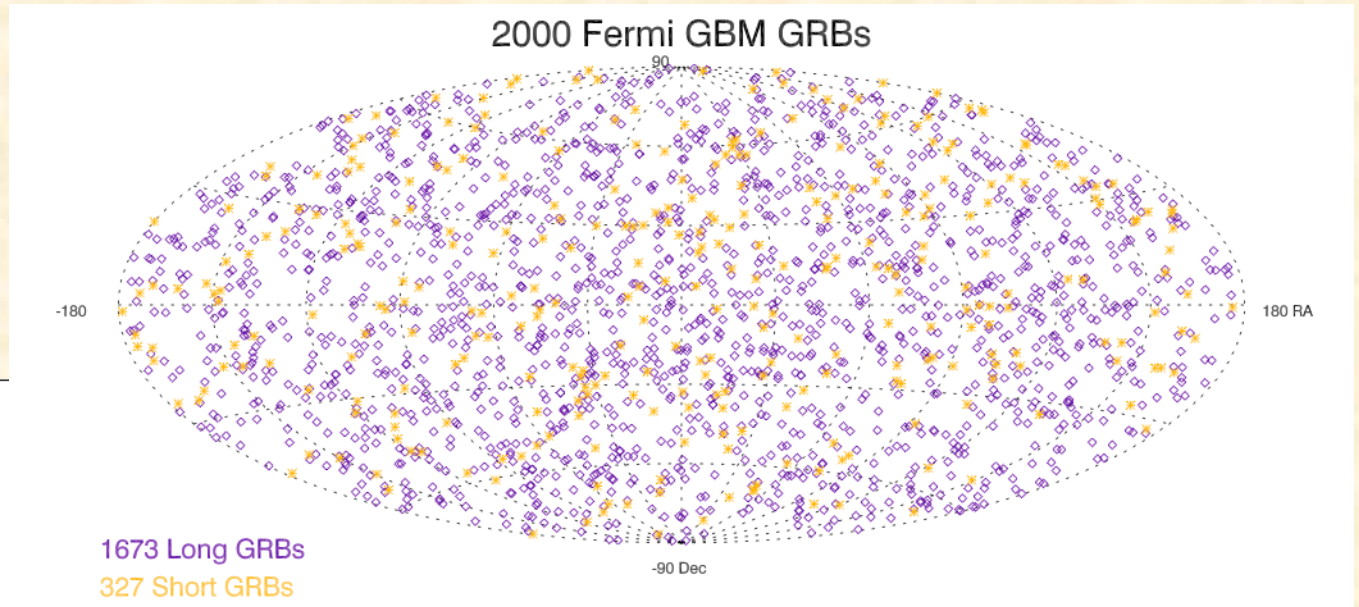
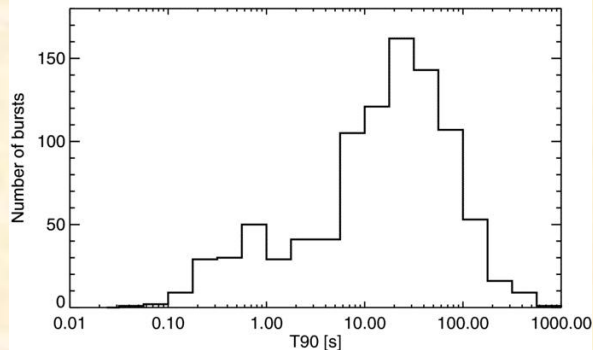
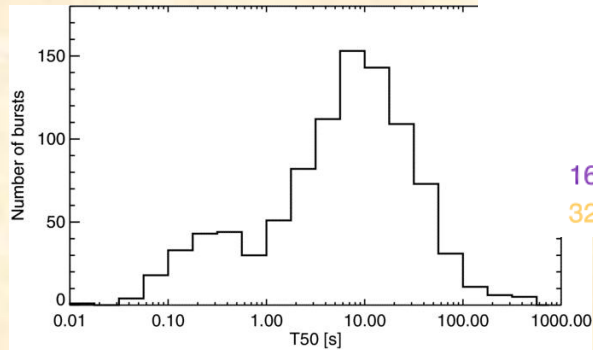
In Field-of-view of LAT (1045)

Out of Field-of-view of LAT (955)

52% in LAT FoV
48% Outside LAT FoV

Short and Long GRBs

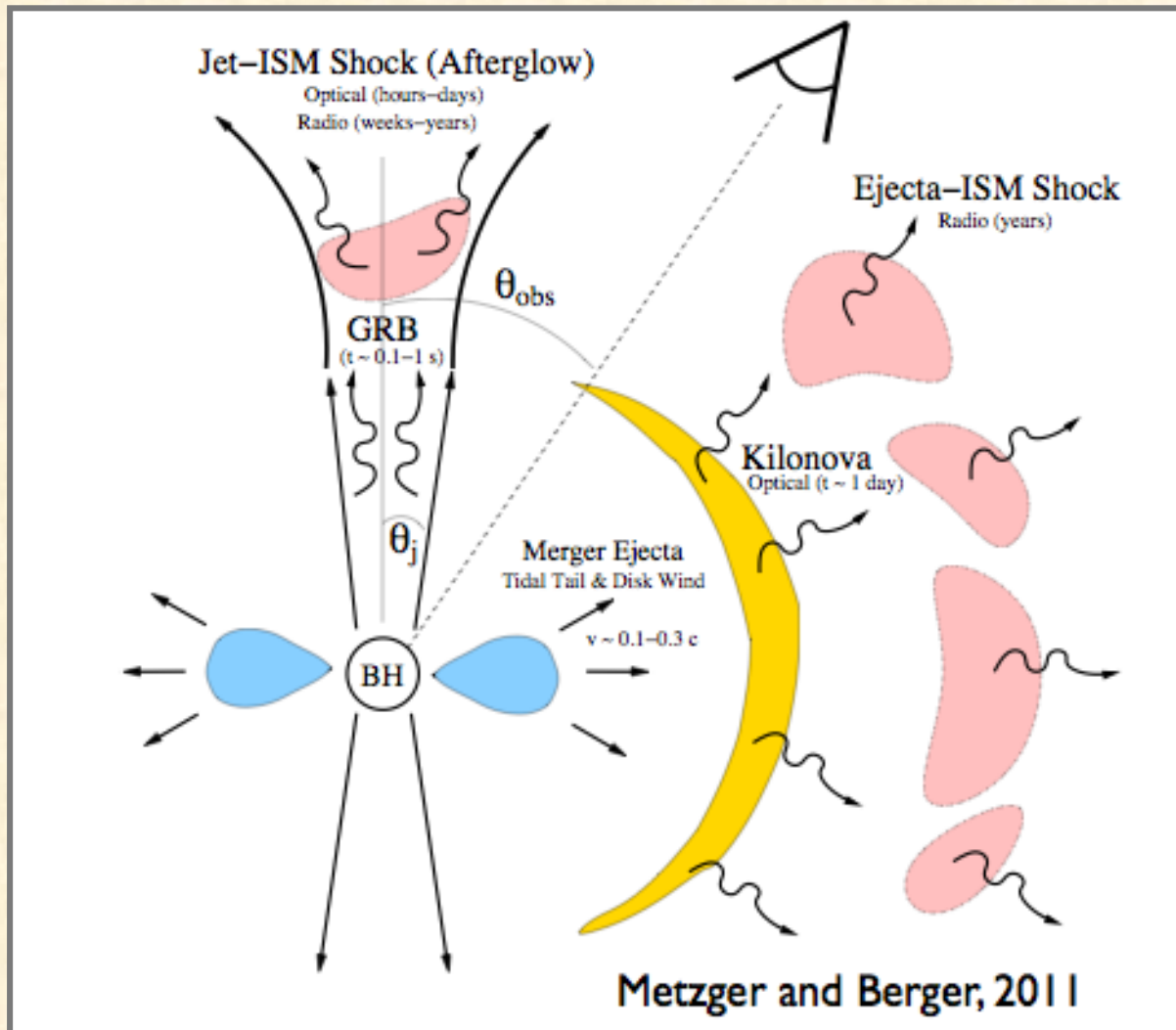
Each year GBM sees:
~200 long GRBs
~40 short GRBs
Swift: ~9 short GRBs/yr



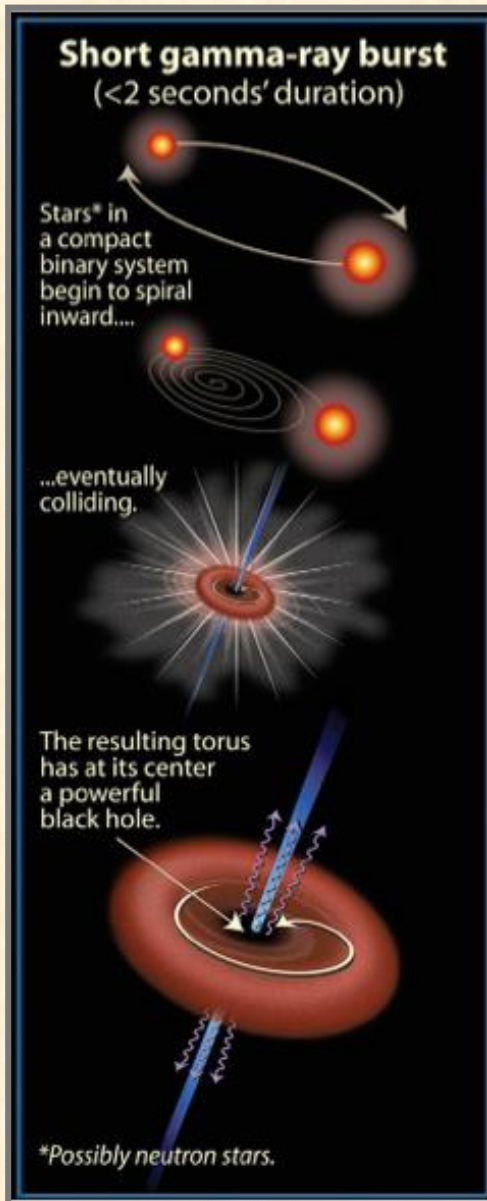
84% of GBM GRBs are long (>2s)
16% are short

GBM is the most prolific detector of short GRBs!

Short GRB / CBC Association



Short GRB / CBC Association



GW

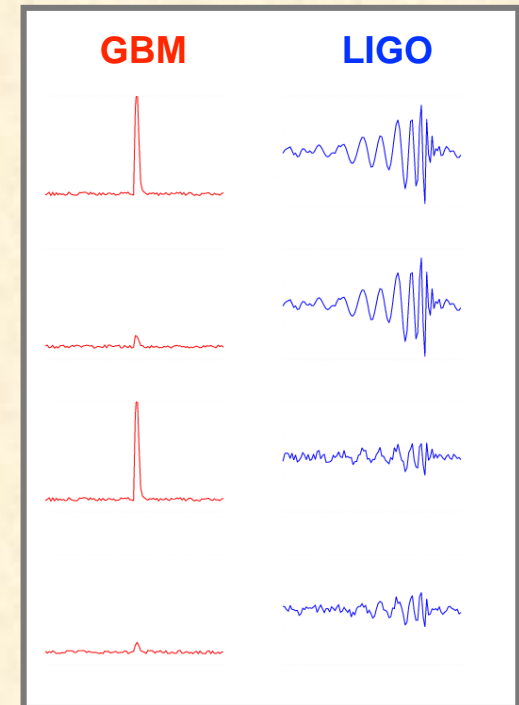
- In-spiral confirms CBC progenitor model
- Information about binary system parameters
- precise merger time
- standard candle -> luminosity distance

EM

- EM energetics
- X-ray or optical afterglow gives precise location
- Breaks degeneracy in binary parameter estimation
- Host galaxy/redshift
- Local environment information
- With many: jet opening angle

Joint Sub-threshold Searches

Ideal Scenario	Bright GBM	Bright LIGO
GW150914 Scenario	Sub-threshold GBM	Bright LIGO
Typical more distant short GRB	Bright GBM	Sub-threshold LIGO
Both Sources Faint	Sub-threshold GBM	Sub-threshold LIGO



The GBM and LIGO teams have been working together to develop automated pipelines to search for sub-threshold signals

In all cases, the presence of a signal in GBM or LIGO, can raise the significance of the signal being real in the other instrument.

A confident gamma-ray signal enables detecting a fainter gravitational wave signal, increasing the GW detection distance limit, in turn increasing the event rate by a factor of the distance cubed

GBM Ground Searches

- Un-targeted search
 - Looks for signals too faint to trigger on-board
 - Needs no input from other instruments
- Targeted search
 - Seeded with a time and optional sky map
 - Inputs generally from LIGO, neutrino detections, etc.
- X-ray Burst search
 - Manual search, resulting from data cleaning for pulsar monitoring

Un-targeted Search (1)

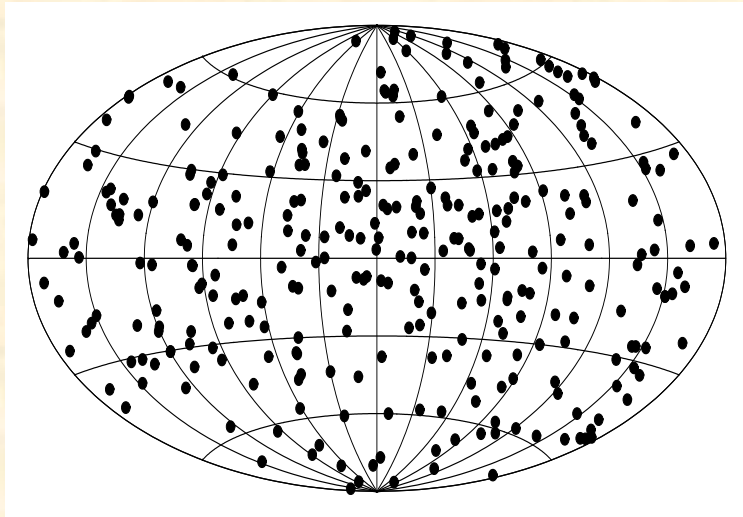
- https://gammamray.nsstc.nasa.gov/gbm/science/sgrb_search.html
- Developed to search for faint short GRBs
- Uses CTTE data, $2\mu\text{s}$ time resolution, 128 energy channels
- 18 timescales: 64 ms to 32s
 - On-board: 16 ms to 8.096 s
- Time series are made 4 times, offset in phase
- 5 energy ranges (optimized on triggered sGRBs)
- Fit a background using cubic splines and filter out bad background fits
- Fast, efficient, runs on hourly CTTE data as it arrives

Un-targeted Search (2)

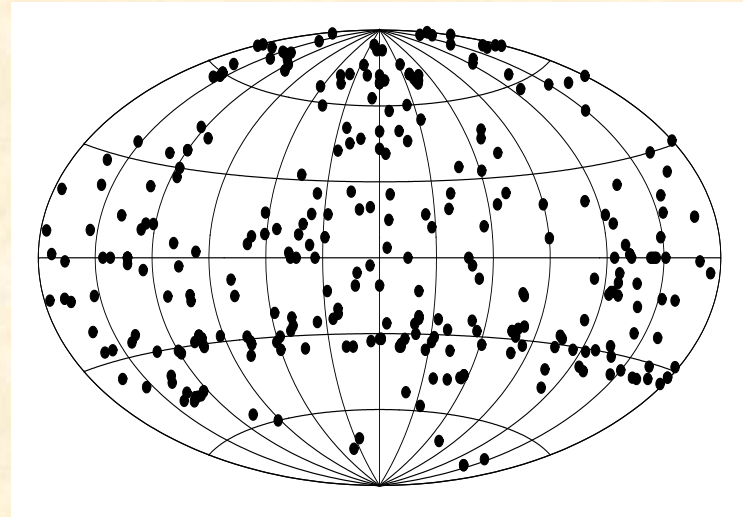
- Test for statistically significant excesses in two NaI detectors:
 - Require $\geq 2.5\sigma$ in the best NaI detector & $\geq 1.25\sigma$ in the second best NaI detector,
 - Require Poisson probability $\leq 1\text{E-}6$, including trials factor for Nbins in one day,
 - Other trials factors not included.
- Require the detector pair be valid for a distant point source.



Un-Targeted Search Results



Galactic coordinates

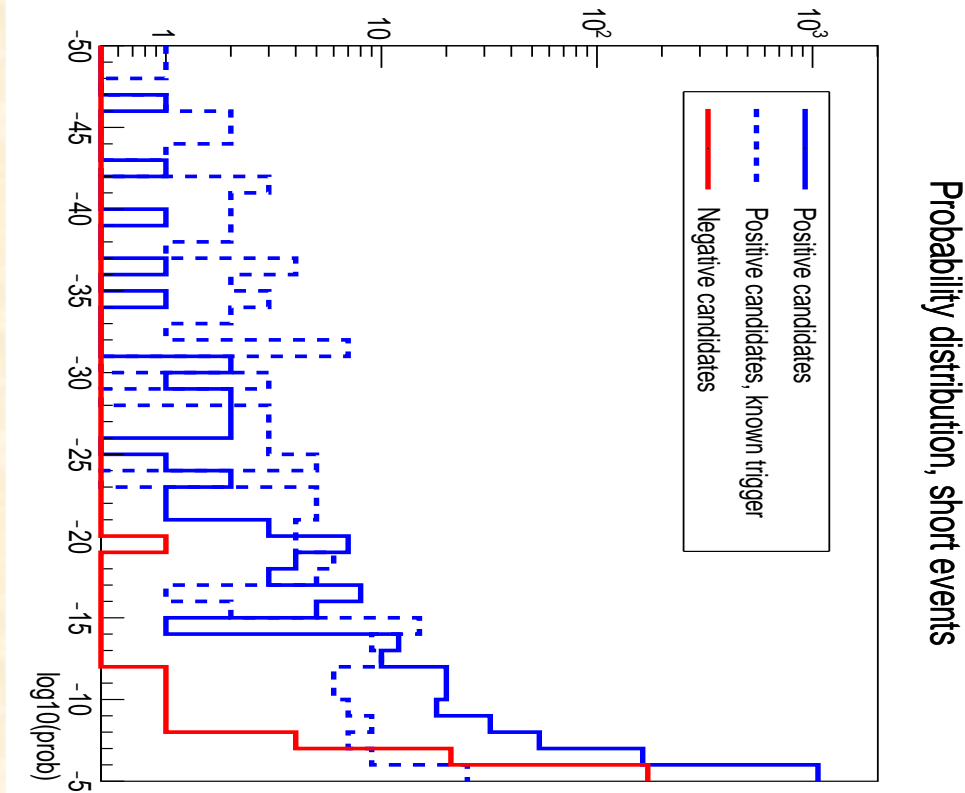


Spacecraft Coordinates

318 short, hard candidates (known triggers omitted) in 46 months.
~80 per year, twice the rate of GBM triggered sGRBs.

Verification 1/2

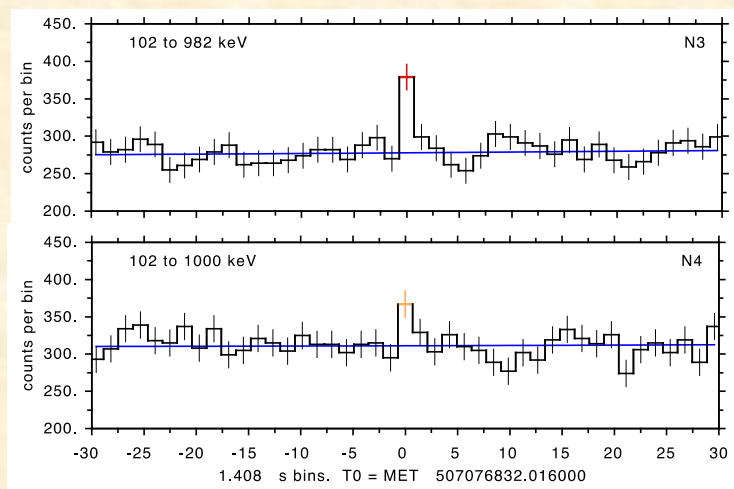
Positive candidates
(blue) versus
Negative deviations
(red)



↑ Current threshold: $1\text{E-}6$

Un-Targeted Search Verification

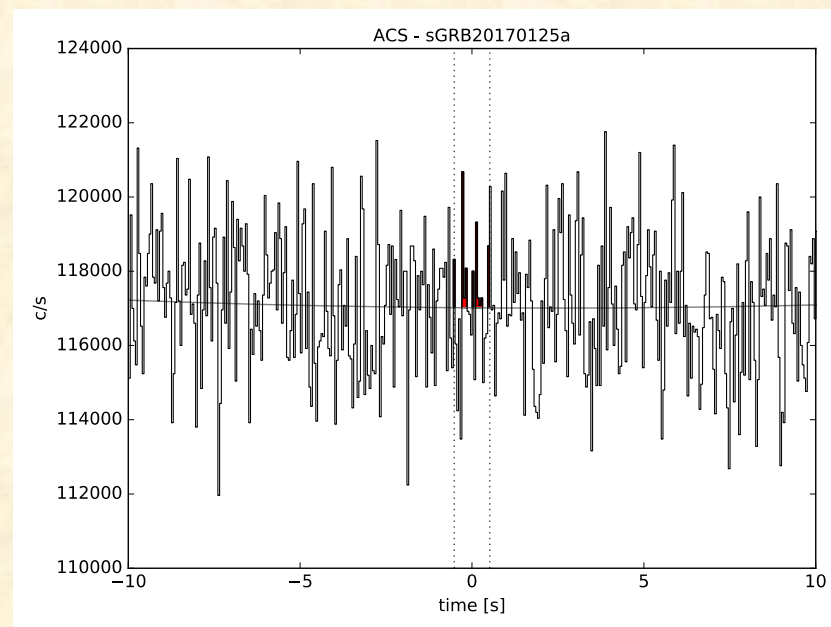
- ~1/4 have signals in more than 2 GBM detectors.
- Swift GRB 140606A: not a GBM trigger, easily detected at $P = 1\text{E}-20$.
- INTEGRAL Anti-Coincidence Shield (ACS):
 - ~1/3 of spectrally-hard candidates are detected by the ACS
 - GBM triggered sGRBs: ~50% detected with the ACS.



6.1σ

3.2σ

A very average candidate: signal in only two detectors & $P=2\text{E}-7$.

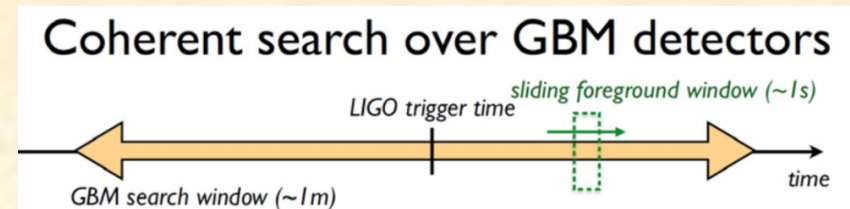


Not detected in INTEGRAL ACS

Targeted Search of GBM data to GW events

- Developed during LIGO S6 observing run (Blackburn et al. 2015, Goldstein et al. 2016)
- Coherent search over all 14 GBM detectors (Nal and BGO)

- seeded with time & (optionally) sky location of any LIGO/Virgo candidate event
- over user-specified time window (± 30 s)
- estimate of background rate by polynomial to local data outside the foreground interval



- ◆ For each template spectrum (soft, medium & hard) and sky location
 - Each model spectrum is folded through the detector response to determine detector counts
 - Detector counts for each energy channel are weighted according to the modeled rate
 - and inverse noise variance due to background
 - Weighted counts from all Nal and BGO detectors are summed to obtain a signal-to-noise optimized light curve for that model
 - Each model is assigned a likelihood by the targeted search based on the foreground counts
- ◆ Candidates are ranked by a Bayesian likelihood statistic
- ◆ Will reveal short-duration candidates between 0.256 s to 8.192 s (CTIME)

GW150914-GBM

Targeted search around GW150914:

- Initial 60s (± 30 s) search window (selected a priori)
- 2 candidates
 - Soft transient: $T_{\text{GW}} + 11$ s, 2s long: Gal.Cent. region
 - Hard transient: $T_{\text{GW}} + 0.4$ s, 1s long: GW150914-GBM

TITLE: GCN CIRCULAR
NUMBER: 18339
SUBJECT: LIGO/Virgo G184098: Fermi-GBM ground-based follow-up
DATE: 15/09/20 01:46:08 GMT
FROM: Lindy Blackburn at CfA <lindy.blackburn@ligo.org>

Lindy Blackburn (CfA), Michael S. Briggs (UAH), Eric Burns (UAH), Jordan Camp (NASA/GSFC), Nelson Christensen (Carleton College), Valerie Connaughton (USRA), Adam Goldstein (NASA/MSFC), Tyson Littenberg (UAH), John Veitch (Birmingham), Judith Racusin (NASA/GSFC), Peter Shawhan (UMD), Leo Singer (NASA/GSFC), Binbin Zhang (UAH)

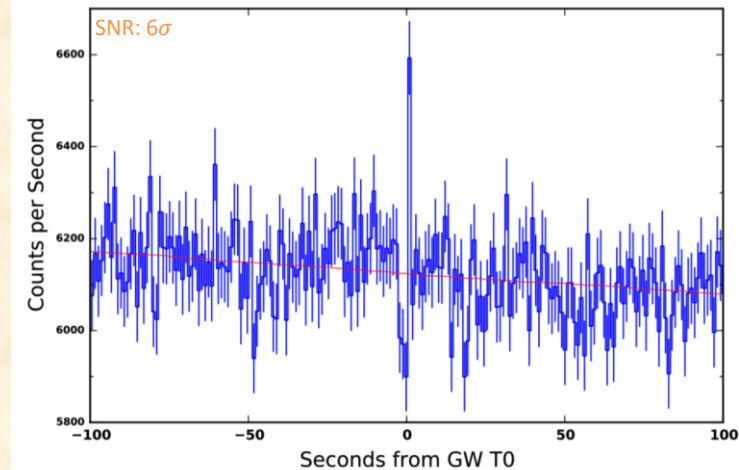
We report on a sub-threshold targeted followup of LIGO candidate event G184098 in Fermi-GBM survey data for bursts between 0.256s and 8s in duration, and covering a range of GRB spectral models. Although there was no on-board GBM trigger at the time of the event, Fermi-GBM was exposed to a large fraction of the LIGO sky position and thus we searched offline data for untriggered events. The GBM FOV is blocked by the Earth which occults 67 degrees from (RA, DEC) = (355.14, -21.23). Thus GBM observation is able to cover about 87.8% of the cWB sky posterior, and 91.5% of the LIB posterior. We scanned several minutes of GBM live-time centered on the GW event time using a pipeline developed specifically for following-up LIGO-Virgo events in GBM archival data during the LIGO-Virgo S6/VSR3 run [1].

The search identified a possible transient beginning at 150914 09:50:45.8, about 0.4s after the reported LIGO burst trigger time of 09:50:45.39, and it lasted for about 1 second. The intrinsic time resolution for this search was 0.256s. Of the three GRB model spectra tested in the search, the event was best matched to the one corresponding to the hardest spectrum. Using GBM

Raw count rates:

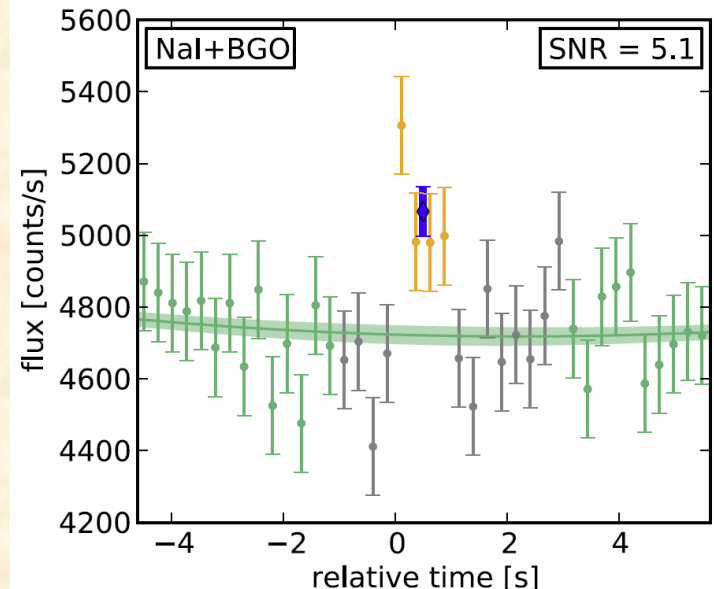
Sum of all GBM detectors: 12 x NaI + 2 x BGO

NaI: 50–980 keV / BGO: 420 keV – 4.7 MeV



Model-dependent count rates:

Raw count rates weighted & summed to max signal-to-noise for a modeled source



GW150914-GBM

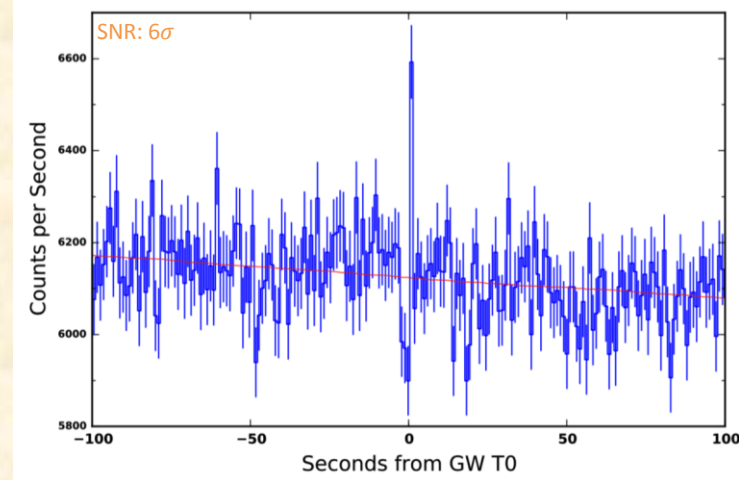
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- Initial 60s (± 30 s) search window (selected a priori)
- 2 candidates
 - Soft transient: $T_{\text{GW}} + 11$ s, 2s long: Gal.Cent. region
 - Hard transient: $T_{\text{GW}} + 0.4$ s, 1s long: GW150914-GBM
 - 0.2% probability of occurring by chance (2.9σ)

Raw count rates:

Sum of all GBM detectors: 12 x NaI + 2 x BGO

NaI: 50–980 keV / BGO: 420 keV – 4.7 MeV



False Alarm Probability Calculation:

False Alarm Rate (FAR) = 27 hard events in 218821.1 s of GBM live time, factor of 3 for spectra searched, 90% confidence

$$P = 2 \times (4.79 \times 10^{-4} \text{ Hz}) \times 0.4 \text{ s} \times (1 + \ln(30 \text{ s} / 0.256 \text{ s})) = 0.0022$$

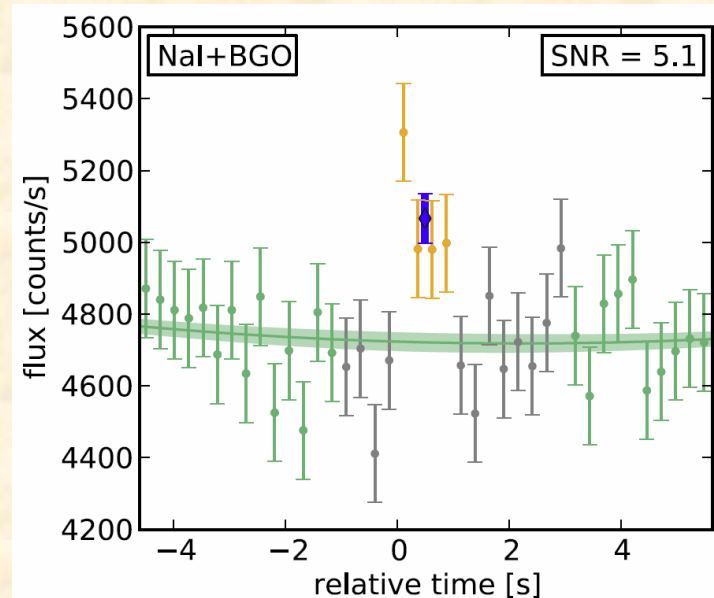
Offset between GW T0 and GBM event start

Factor of 2 to account for offset in time in either direction

Effective trials factor for bins/durations
Searched:
30 s: max offset (search window)
0.256 s: min CTIME bin

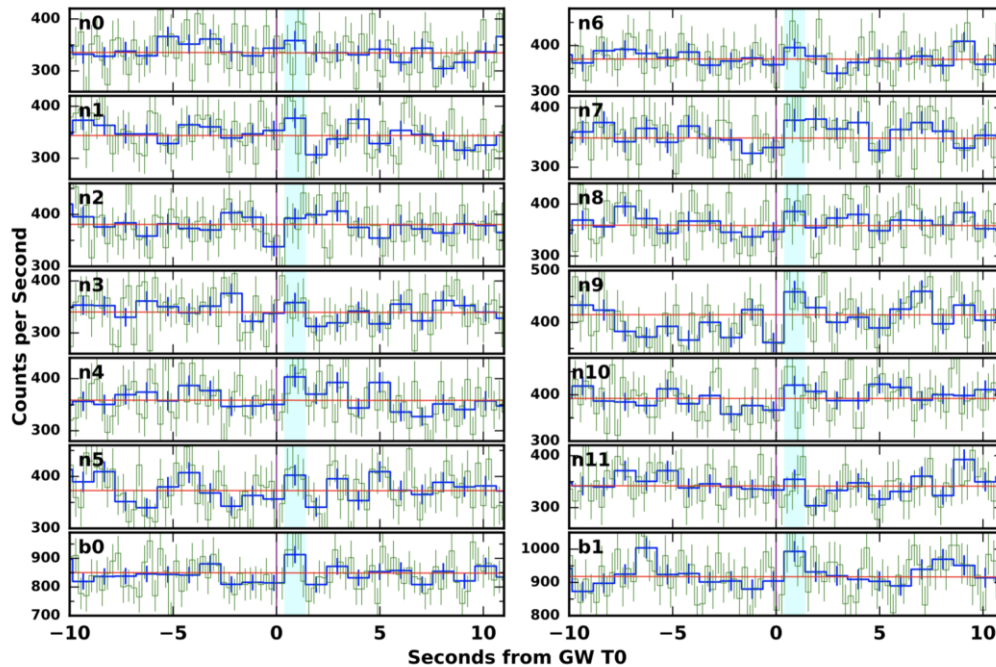
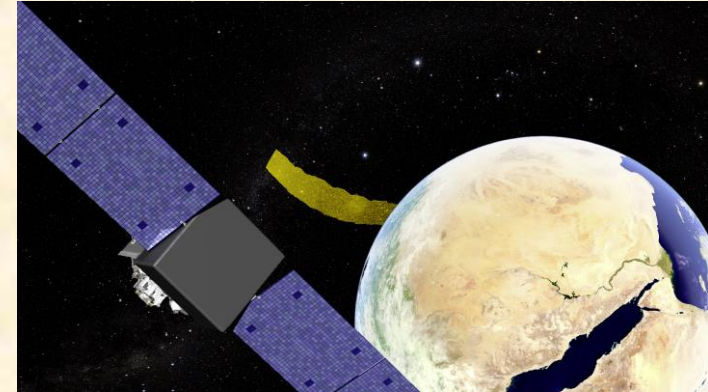
Model-dependent count rates:

Raw count rates weighted & summed to max signal-to-noise for a modeled source

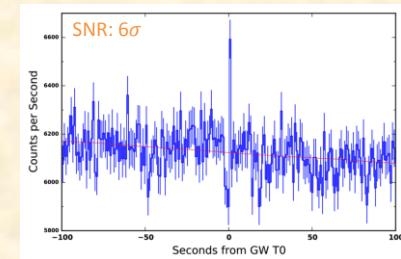


Characteristics of GW150914-GBM

- Unusual detector pattern:
nearly equal count rates in all NaI detectors
 - Localization: source direction underneath the spacecraft, 163° to the spacecraft pointing direction



Nals:
50 – 980 keV
BGOs:
420 keV – 4.7 MeV

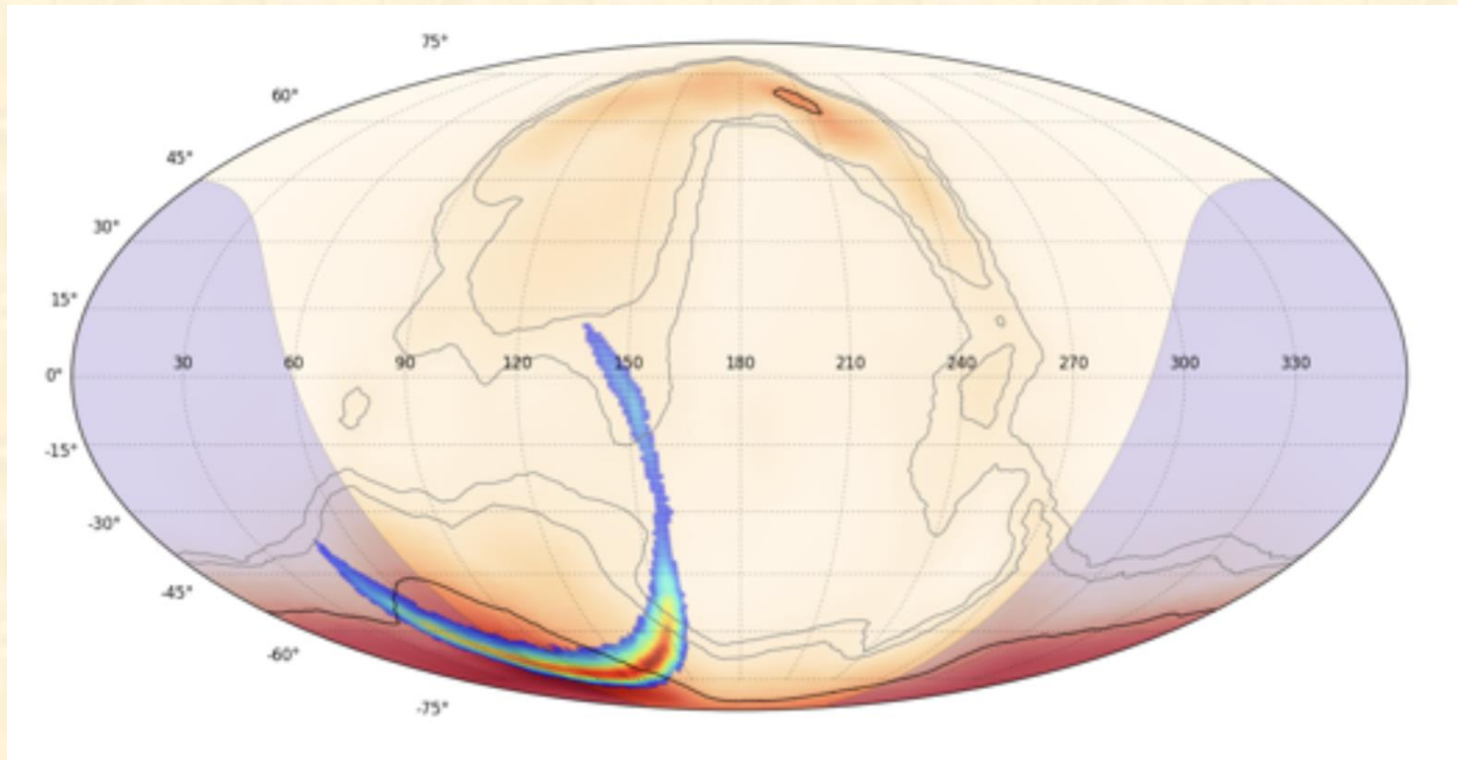
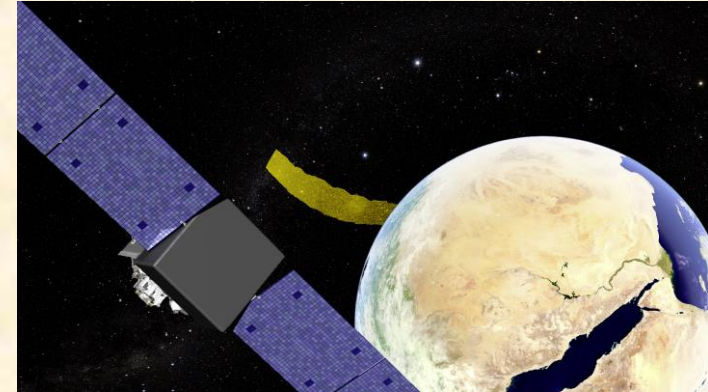


σ deviation from a background fit

NaI 0	NaI 1	NaI 2	NaI 3	NaI 4	NaI 5
1.31	1.81	0.64	1.05	2.42	1.68
NaI 6	NaI 7	NaI 8	NaI 9	NaI 10	NaI 11
1.31	1.64	1.45	2.20	1.61	0.66
BGO 0	BGO 1				
2.25	2.56				

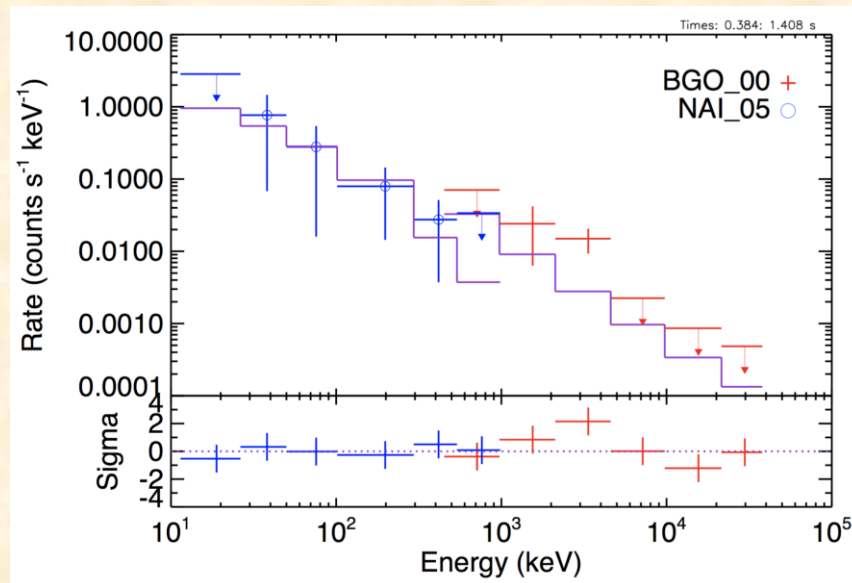
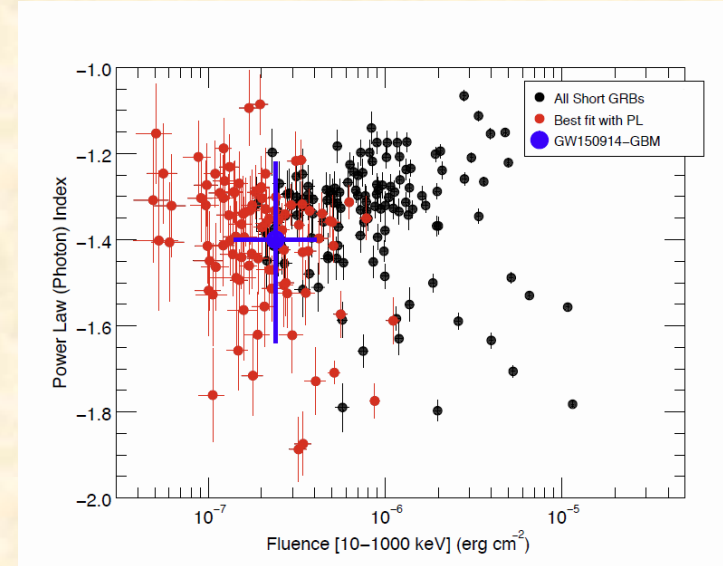
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 - If association with GW150914 was true: shrink LIGO localization by 2/3



Characteristics of GW150914-GBM

- Unusual detector pattern:
nearly equal count rates in all NaI detectors
 - Localization: source direction underneath the spacecraft, 163° to the spacecraft pointing direction
 - If association with GW150914 was true: shrink LIGO localization by 2/3
- Energy spectrum:
 - Peaking in BGO energy range
 - Best fit simple PL with index **-1.4** (average for sGRBs), Fluence **$2.4 \times 10^{-7} \text{ erg cm}^{-2}$** (weaker than average for sGRBs)



Association with GW150914?

- Evidence for
 - 3 sigma False Alarm Probability
 - GBM signal localized to a region consistent with the LIGO sky map
 - Cannot be attributed to other known astrophysical, solar, terrestrial or magnetospheric activity
- Evidence against:
 - Low significance
 - Lack of corroboration by other experiments
 - Nature of the LIGO event is a BH-BH merger



	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs/TEBs)	No	No	?	No	No	No
Galactic Sources	?	No	No	?	N/A	No
Solar Activity	?	No	No	No	N/A	No
Magneto-spheric	No	?	?	No	No	No
Something New	?	?	?	?	?	Unlikely.
Short GRB	Yes	Yes	Yes	Yes	N/A	Yes

The most likely explanation is a short GRB ...



GBM Observations of GW Events

GW 150914

(Abbot et al. 2016a)

- BH+BH Merger
- 36 & 29 M_{\odot}
- 410 Mpc

LVT 151012

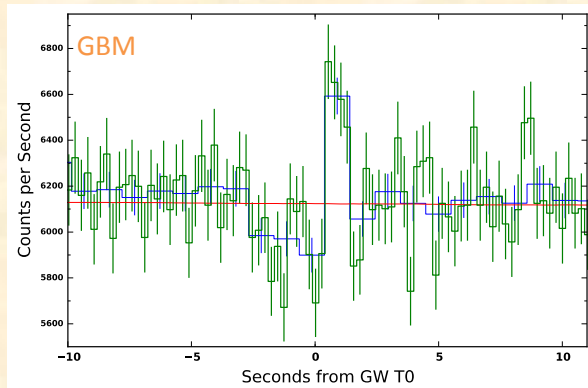
(Abbot et al. 2016a)

- Candidate BH+BH
- 23 & 13 M_{\odot}
- 1100 Mpc

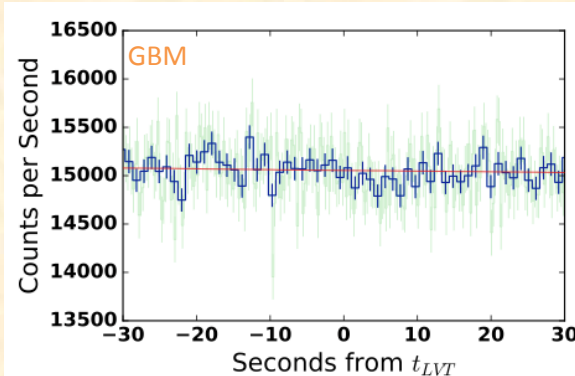
GW 151226

(Abbot et al. 2016b)

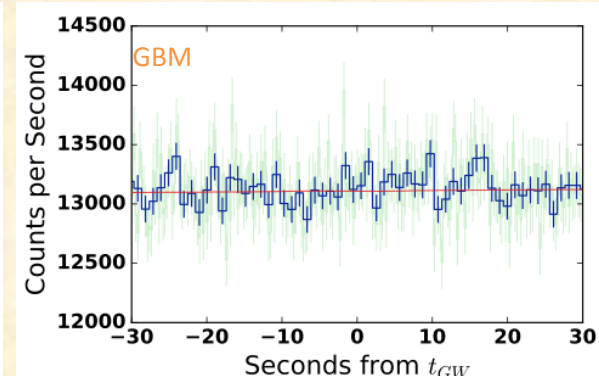
- BH+BH Merger
- 14 & 7.5 M_{\odot}
- 440 Mpc



(Connaughton et al 2016)



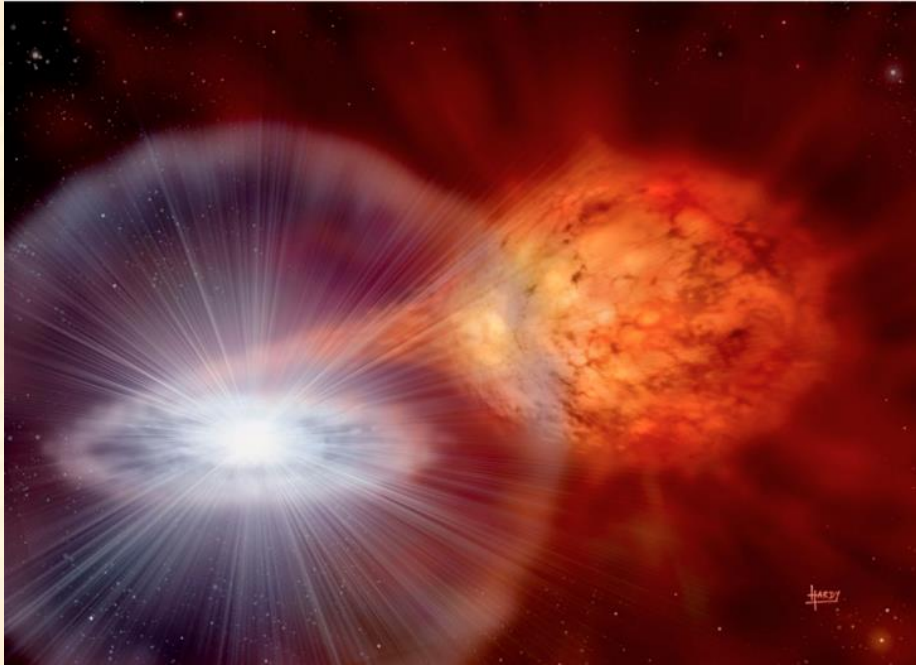
(Racusin et al 2016)



- GW150914-GBM, a 2.9σ event consistent with a short GRB
 - Not predicted by theoretical models
- No gamma-ray detections for LVT151012 or GW151226 – not constraining
 - 32% and 17% of LIGO localization region blocked by Earth for GBM
 - Backgrounds were 18% and 3% higher in GBM
 - Distance for LVT151012 was 3x larger
 - If gamma-ray emission is in a jet, only 15-30% would be pointed toward Earth
- Need more events before we can say more!

Type 1 X-ray Burst

Neutron star accreting matter from a low mass companion at low mass accretion rate.



$$\dot{M} \sim 2\% \text{ Eddington}$$

- Three types
 - Normal
 - 10-100 s
 - H, He
 - $L \sim 10^{39} - 10^{40} \text{ erg/s}$
 - Long
 - 10-30 Minutes
 - He
 - $L \sim 10^{41} \text{ erg/s}$
 - Super
 - Hours – Days
 - C
 - $L \sim 10^{42} \text{ erg/s}$

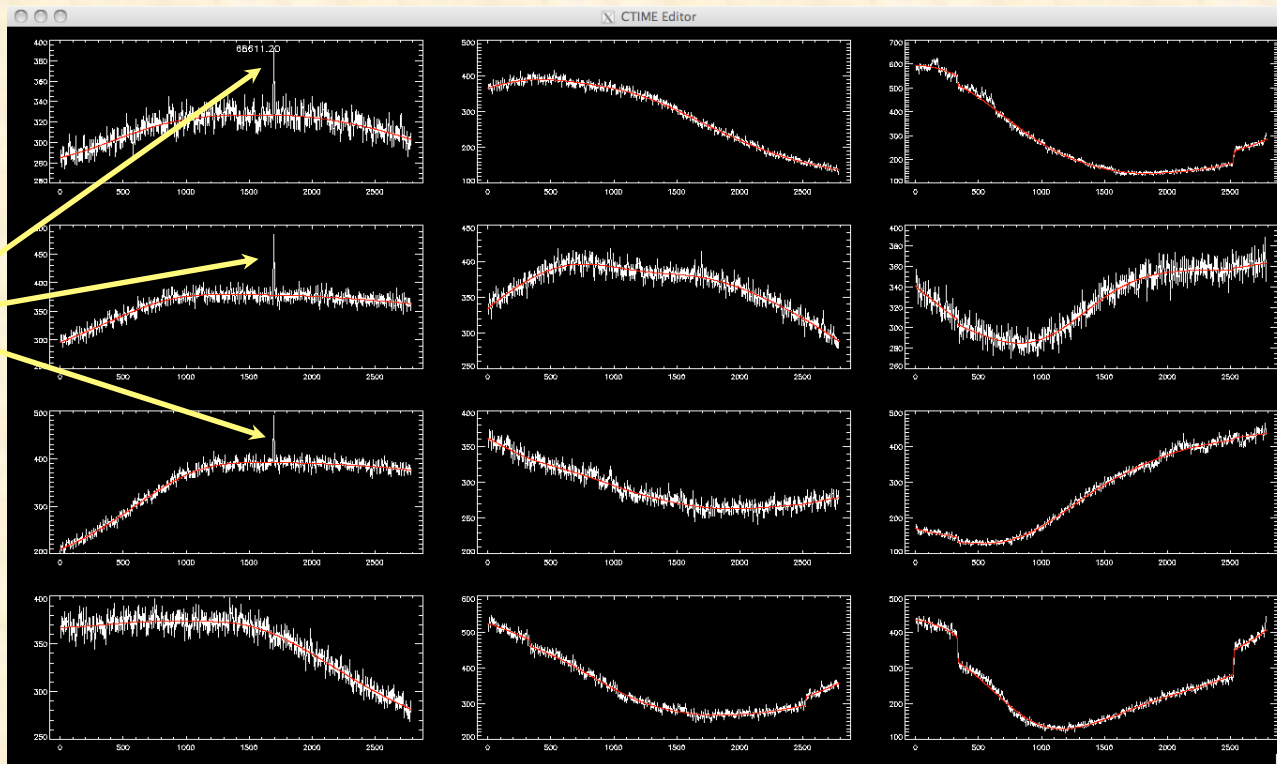
GBM X-ray Burst Search

Visual Inspection of CTIME Data

12 NaI detectors
12-25 keV
8 second bins

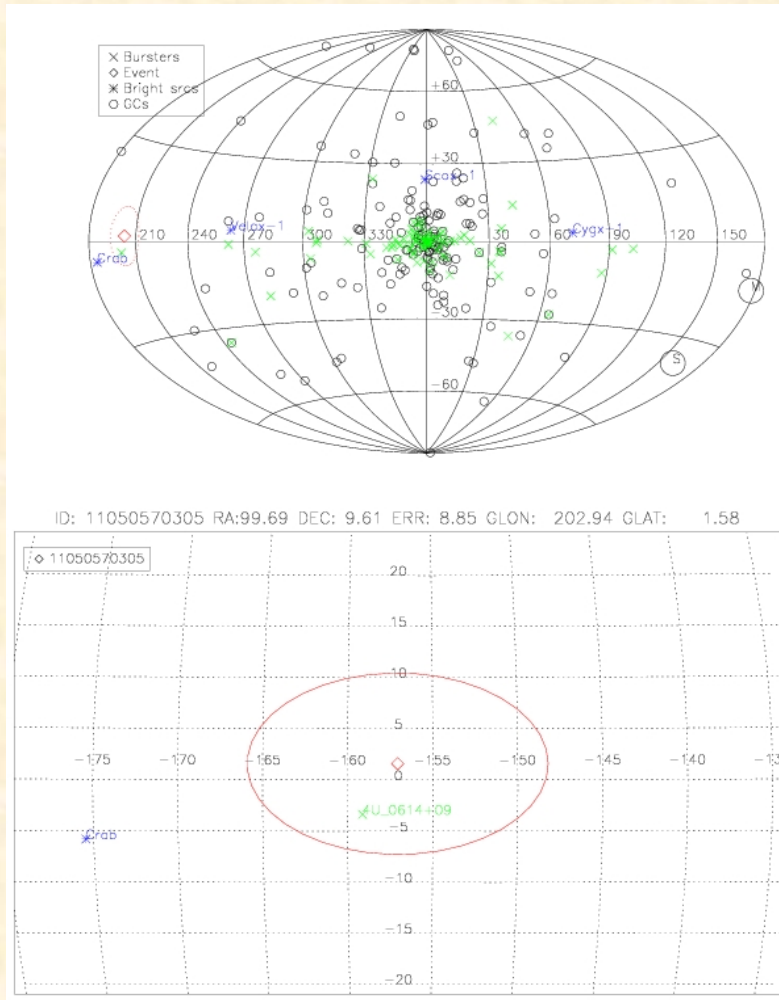
GBM Pulsar Project
PI C. Wilson-Hodge

4U 0614+09



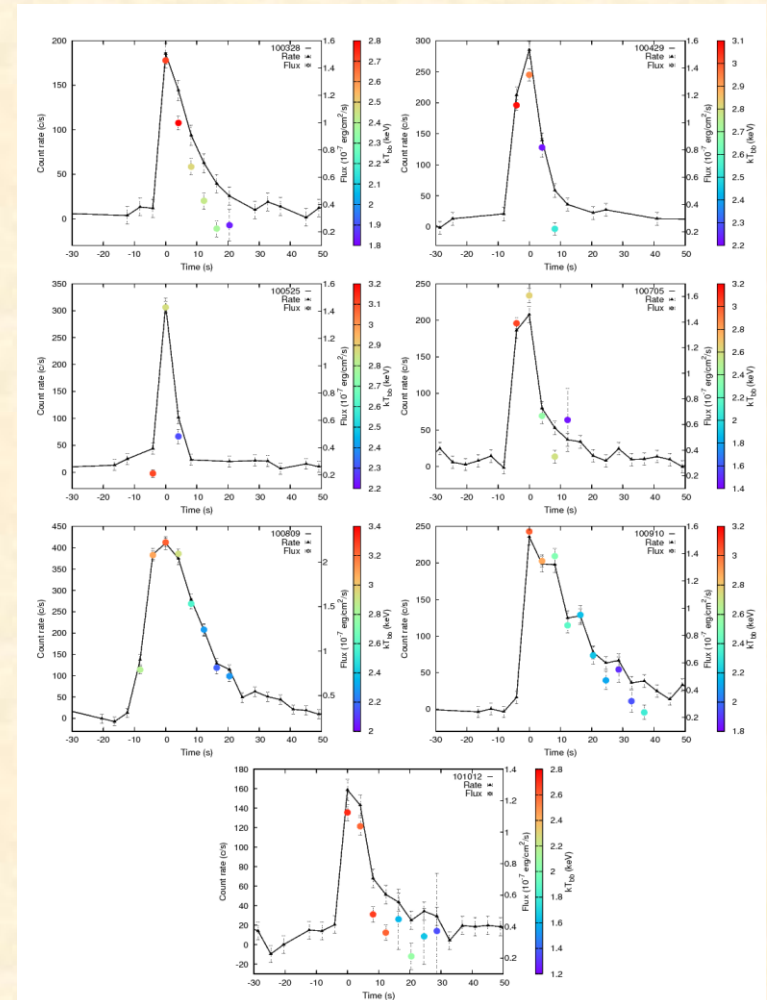
Initiated March 12, 2010

Identification Process



4U 0614+09

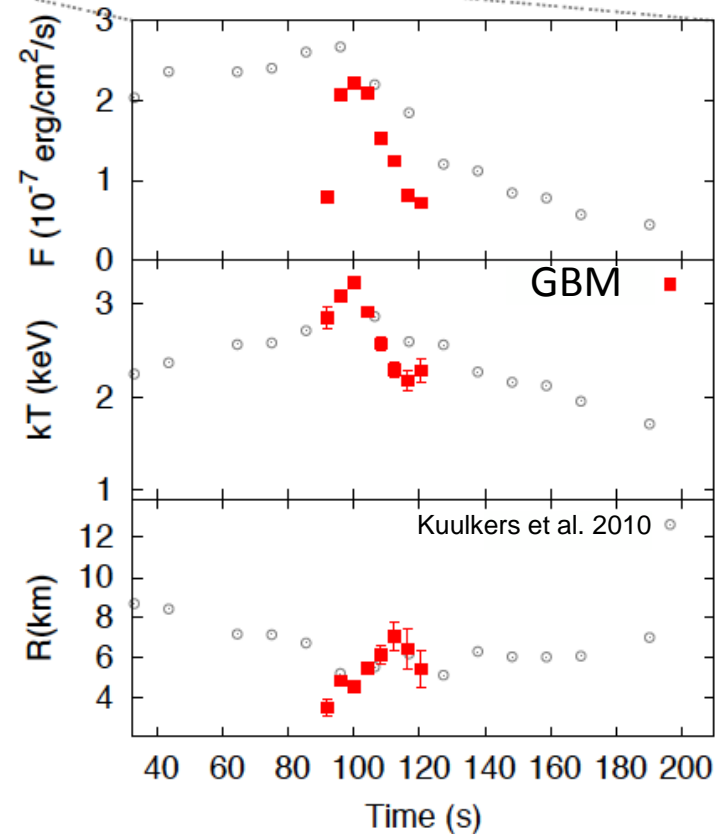
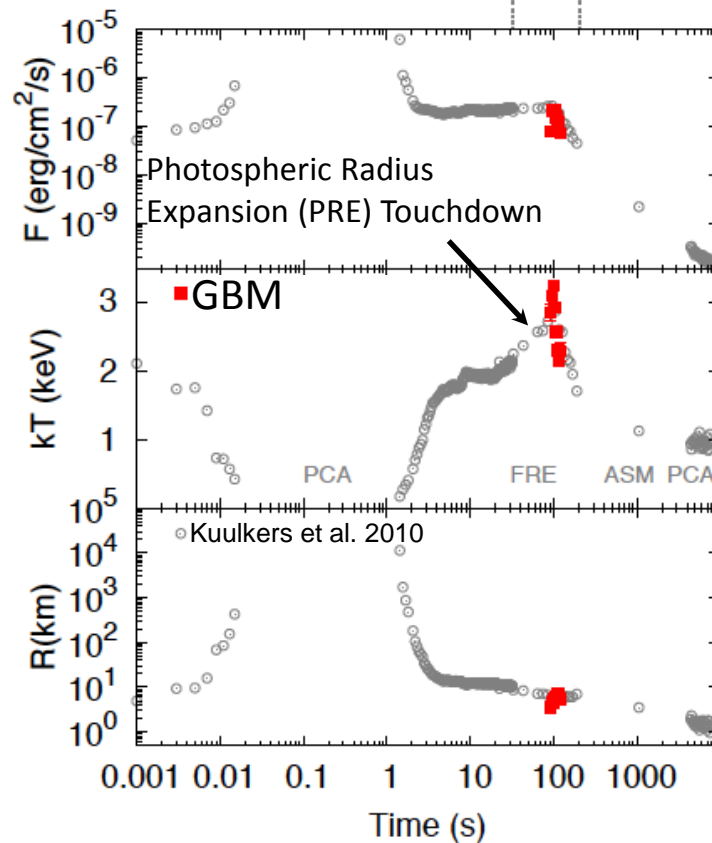
Location



Spectral

What does GBM see?

4U 0614+09



Three Year X-ray Burst Catalog

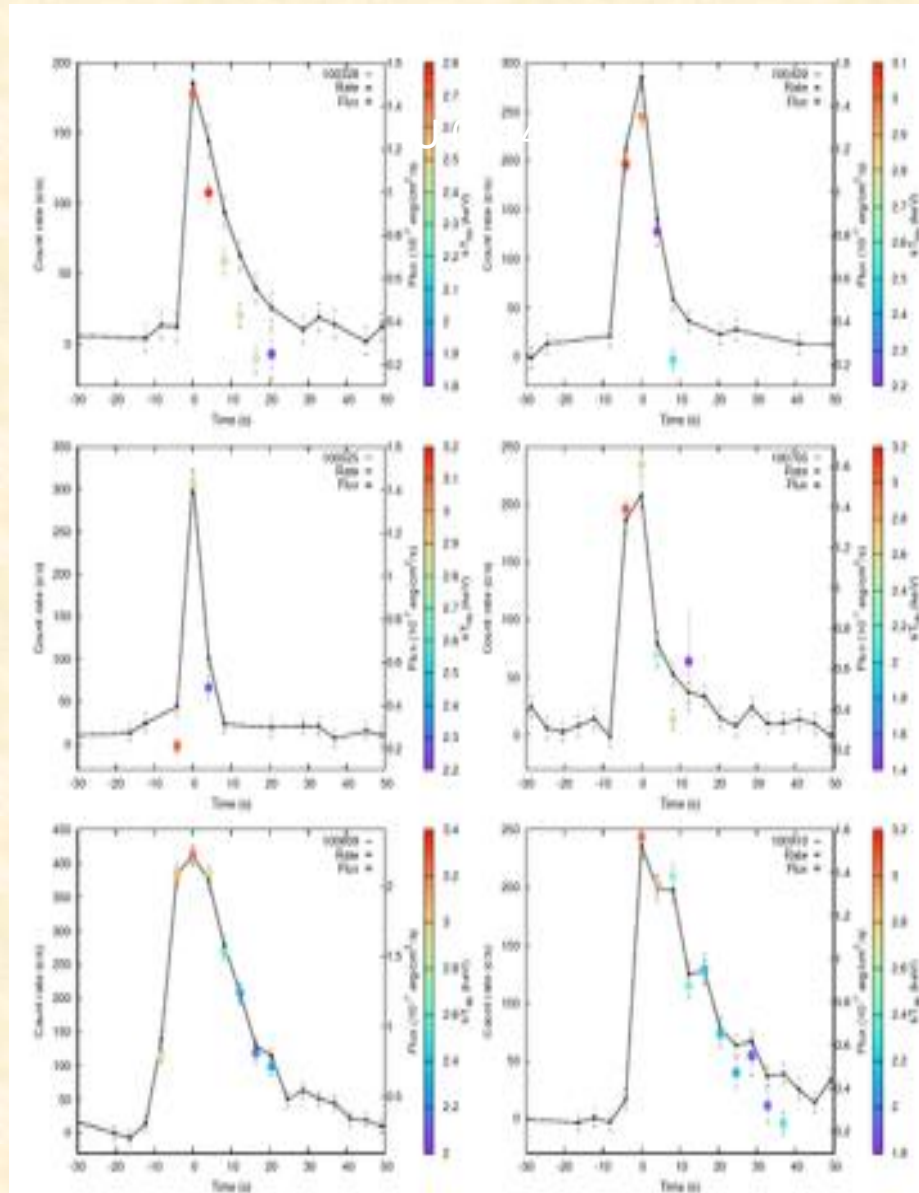
<https://gammaray.nsstc.nasa.gov/gbm/science/xrb.html>

Jenke et al. 2016, ApJ, 826, 228

752 Thermonuclear XRBs
267 Transient Events from accretion flares
65 Untriggered GRBs

GBM is sensitive to photospheric radius expansion (PRE) bursts

1.4 PRE bursts per day within 10 kpc

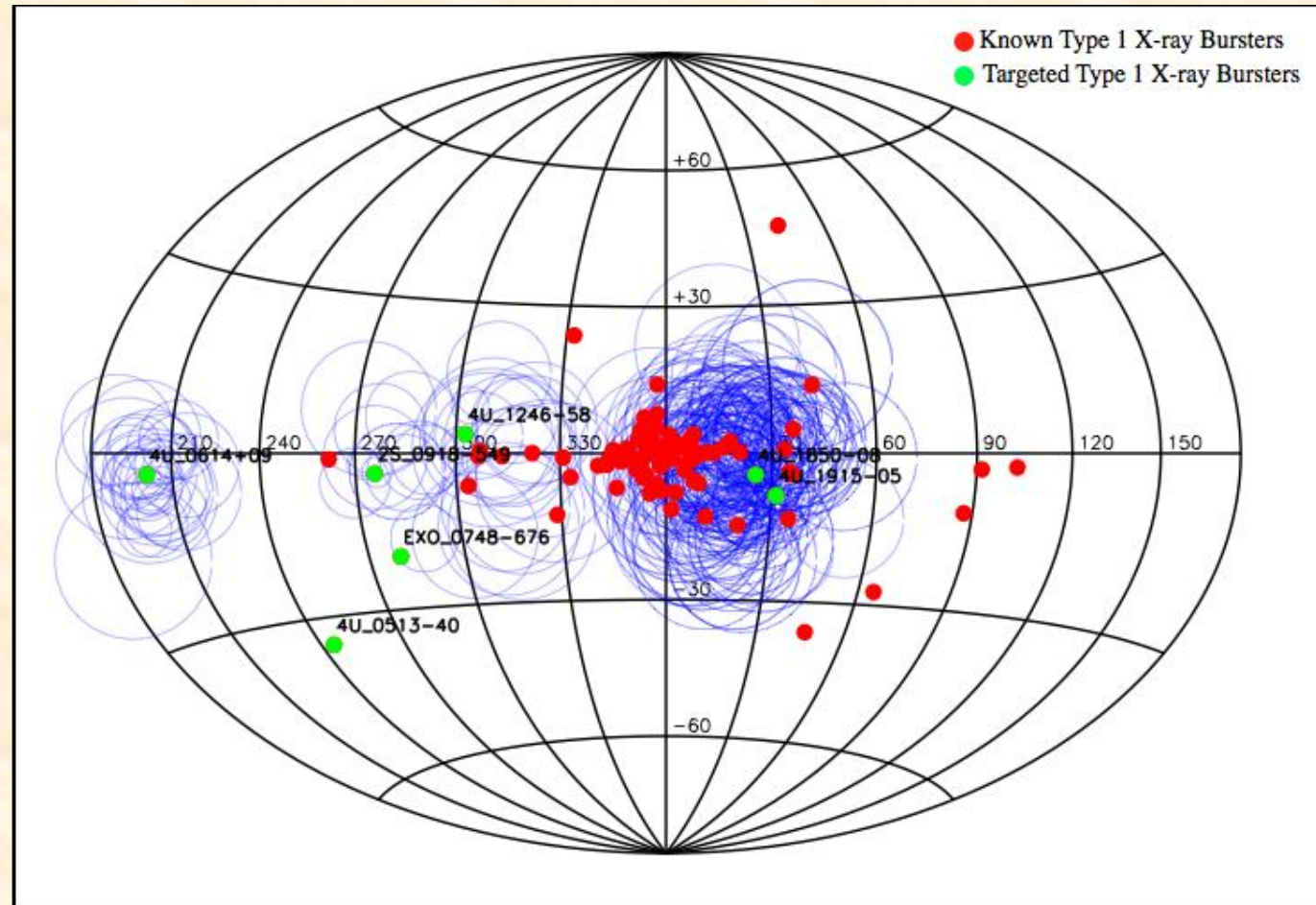


Associations for Low \dot{M} Accretors

Associations For Low \dot{M} Accretors

- 33 - 4U 0614+09
- 10 - 2S 0918-549
- 4 - SAX J1818.7+1424
- 2 - UW Crb
- 2 - IGR J17062-6143
- 1 - XB 1940-04
- 1 - Ser X-1
- 1 - MAXI J1421-613

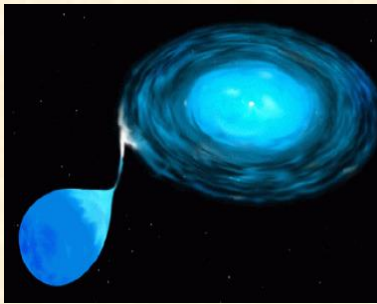
Locations are poor. Must use
MAXI rates to determine if
potential source is active.
Automatic checking.



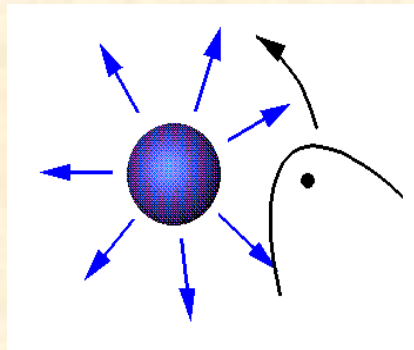
Long Transients (hours to years)

Accretion Powered Pulsar Monitoring

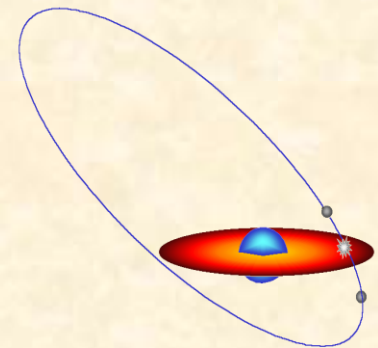
- Blind search
 - For unknown sources and unmonitored transients
- Dedicated search
 - Search around known frequencies
 - Currently monitoring 39 systems (36 detected)
- GBM Advantage
 - Typically $> 40,000$ s of on-source time per day!



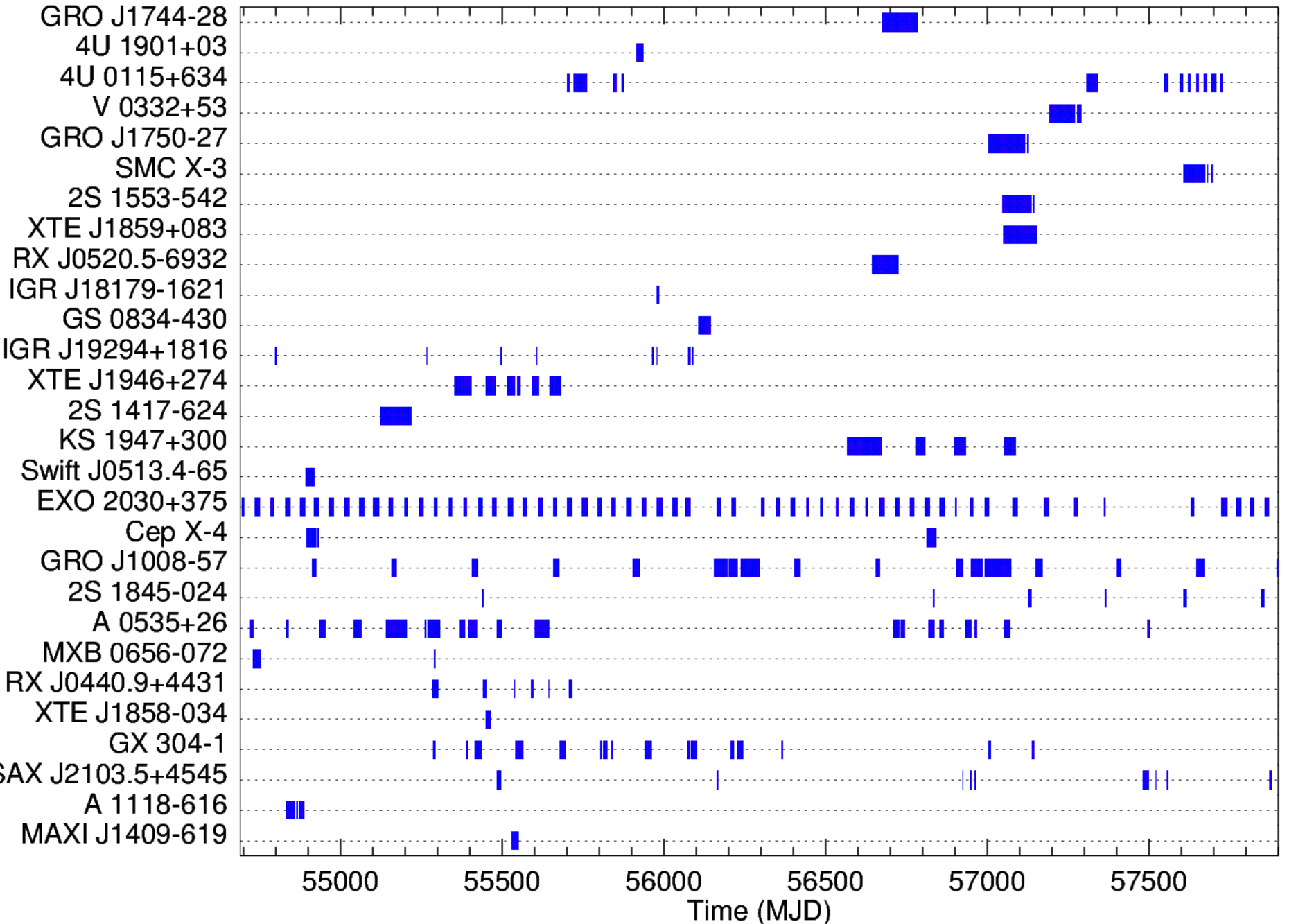
Roche lobe overflow



Wind accretion



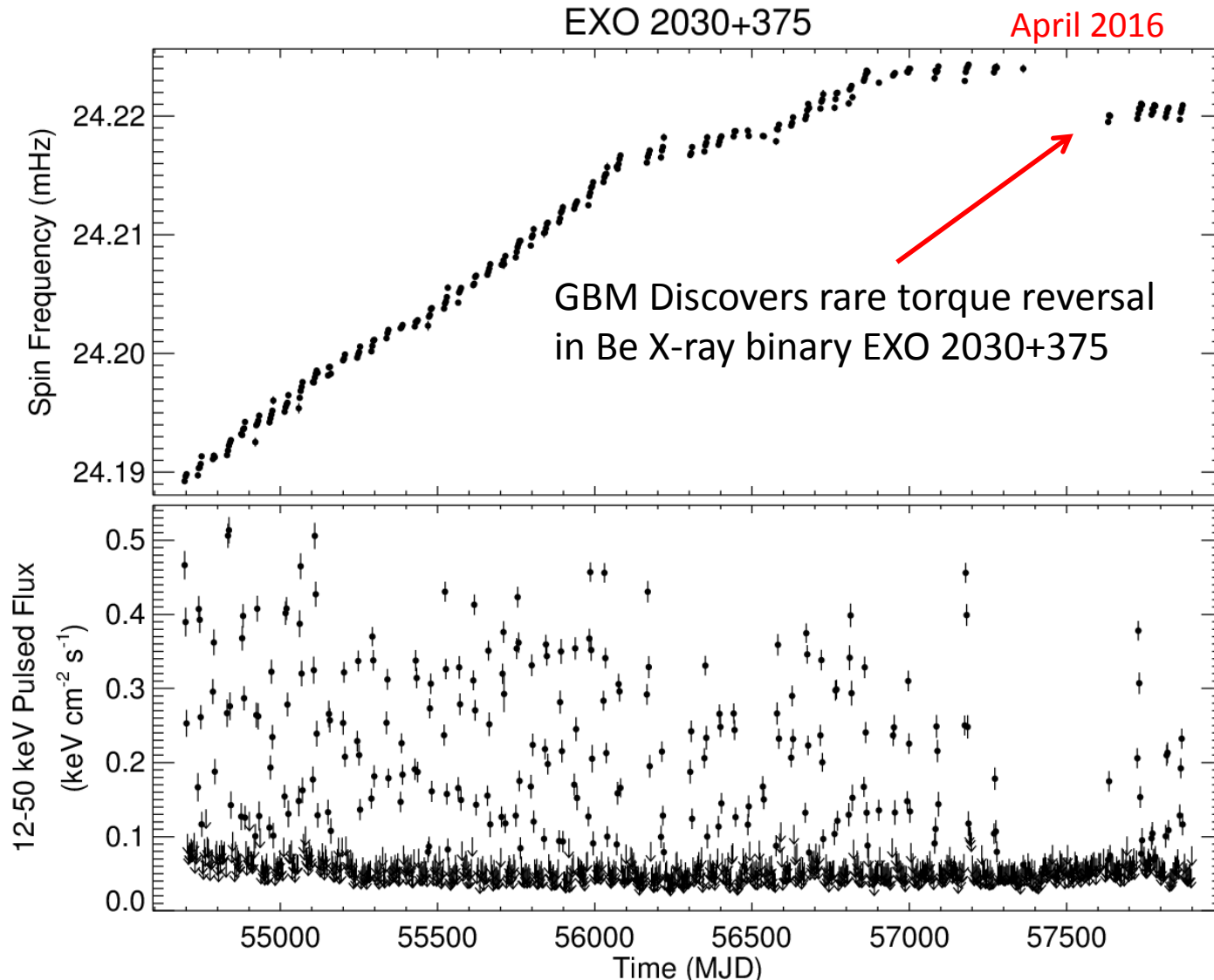
Accretion from a Be star's
circumstellar disk



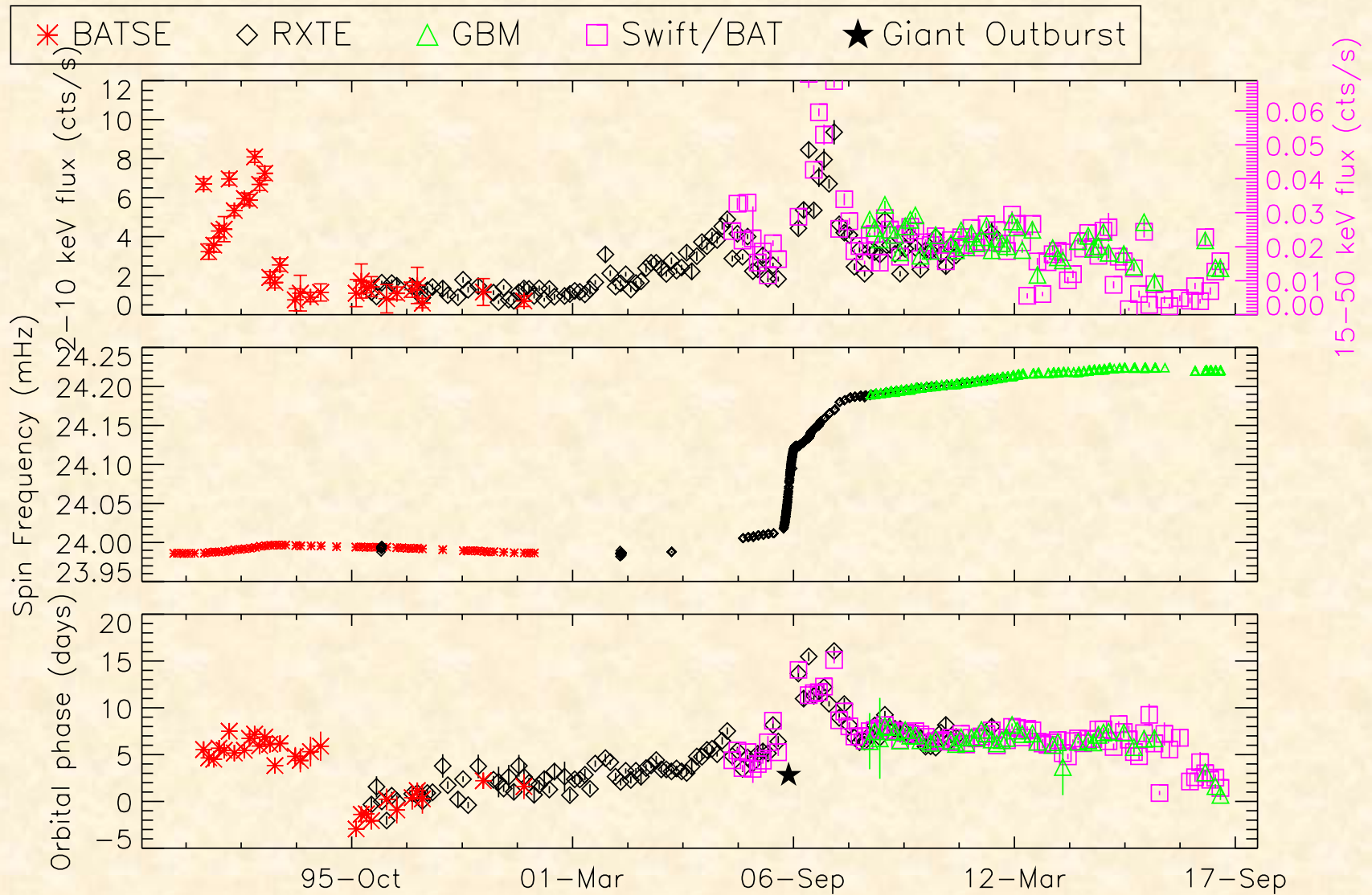
EXO 2030+375 ($P_s=42$ s, $P_{orb}=46$ d)

- Discovered during a giant outburst in 1985 with EXOSAT; Second giant outburst in 2006 (RXTE)
- Transitioned to spin down in 1995 and again in 2016
- Abruptly shifted in outburst orbital phase in 1995 accompanied by a drop in outburst flux; again in 2016
- Detected outburst at nearly every periastron passage since 1991, unlike most Be X-ray binaries
- Correlated peak flux and orbital phase of outburst peak – delay of accretion from Be disk onto NS accretion disk?

EXO 2030+375 Torque Reversal



EXO 2030+375 Long Term Behavior



Orbit Determination – Flux based torque model

Torque Model

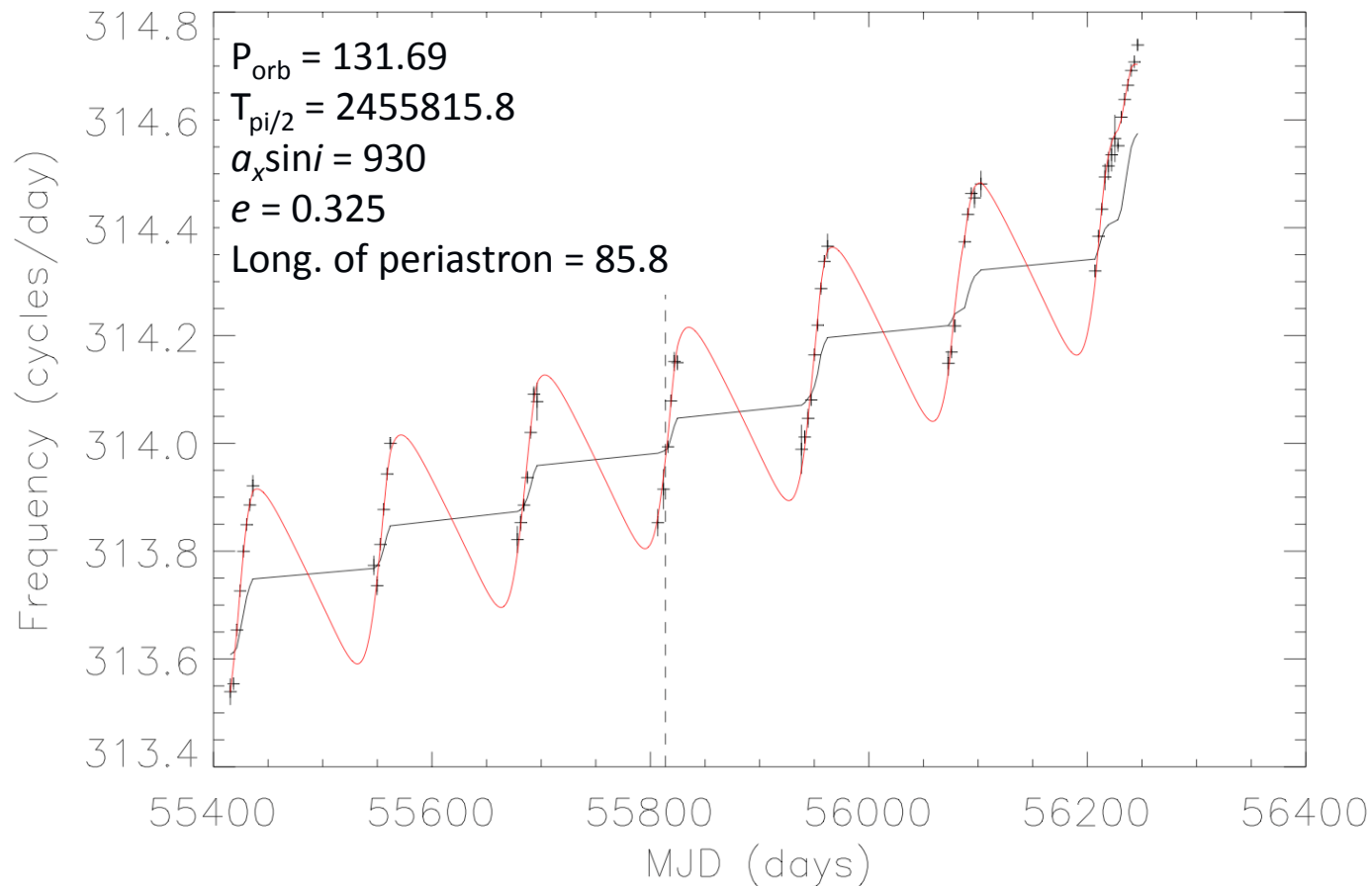
$$\dot{\nu} \propto B^{2/7} F^{6/7}$$

$\dot{\nu}$ = frequency derivative

B = Magnetic Field

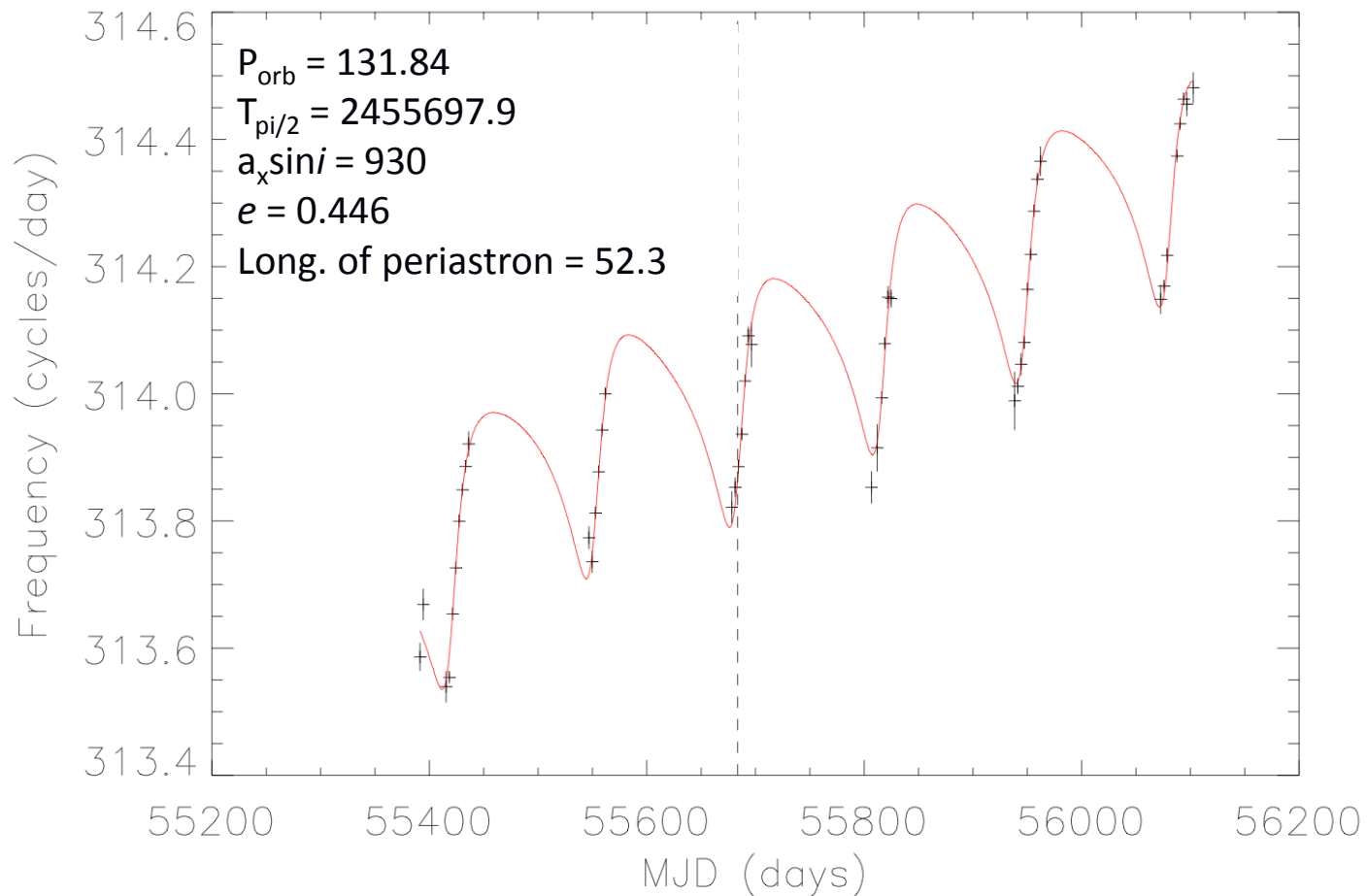
F = X-ray Flux

GX 304-1



Orbit Determination

Polynomial Torque model

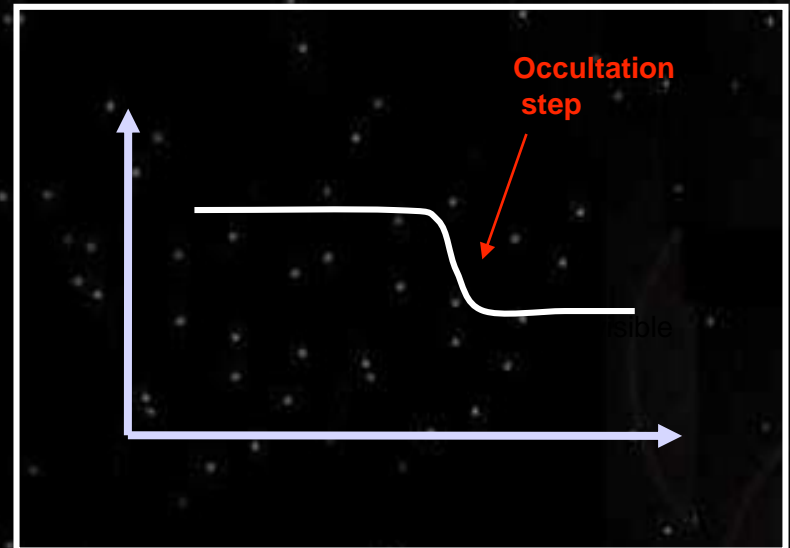


Earth Ocultation with GBM

'Occultation steps' occur in the detector count rates as sources rise above and set below the Earth's horizon...



Crab Nebula
detected to 300 keV



C. A. Wilson-Hodge, P. Jenke, et al., "Three years of Fermi GBM Earth Ocultation Monitoring: Observations of Hard X-ray/Soft Gamma-Ray Sources," ApJS 201, 33 (2012)

GBM Observations of V404 Cyg

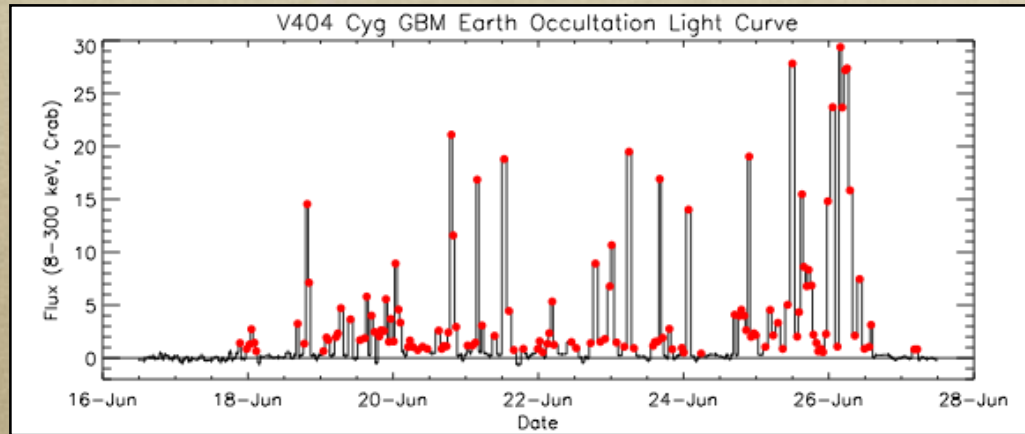
- $10 M_{\odot}$ black hole only 2.4 kpc away
- Last X-ray outburst observed with Ginga in 1989
- Two confirmed optical outbursts in 1938 and 1956
- 169 GBM triggers over 13 days starting June 15, 2013
- 73 distinct flaring episodes
- Reached 30 crab with emission up to 300 keV
- GBM observed the entire outburst. It can be analyzed using both triggered data and Earth occultation

Fermi

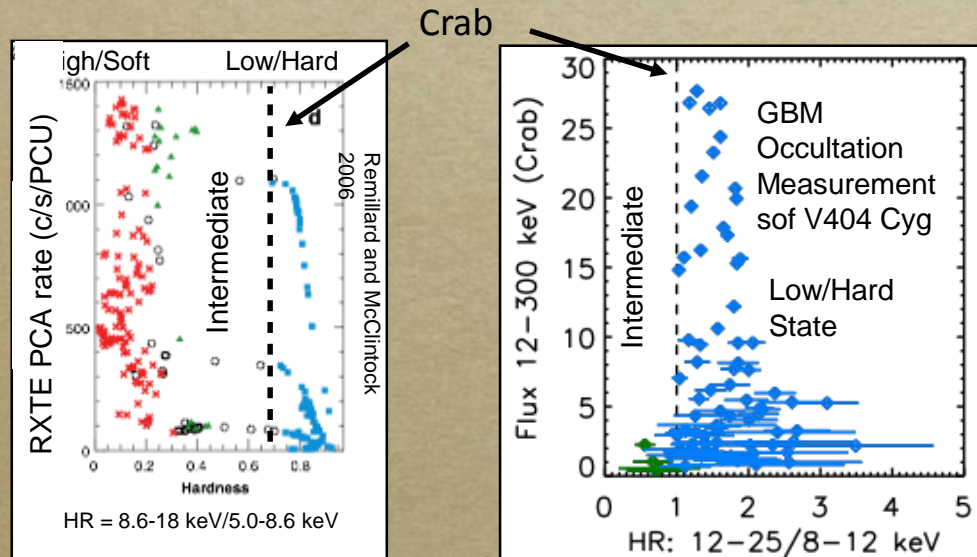
Gamma-ray Burst Monitor



GBM Earth Occultation Results



• > 3 sigma
120 seconds



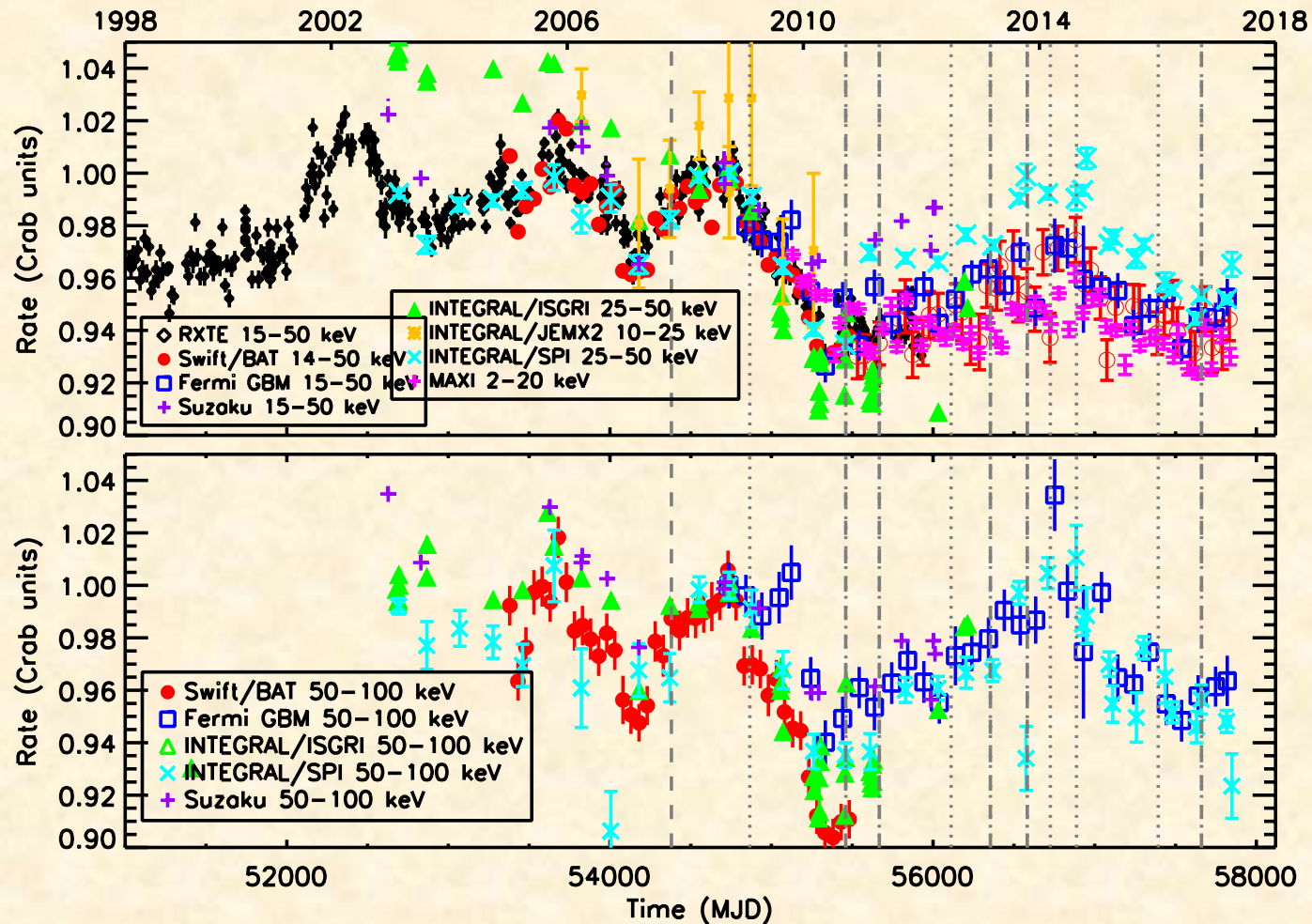
Comparing V404 Cyg to
GX 339-4

V404 Cyg is predominately
in the Low/Hard State

V404 Cyg - Fermi 2015

P. Jenke

Long-term Hard X-ray Variations in the Crab Nebula



Searches for multi-messenger counterparts using Earth occultation

- Using the Earth occultation technique, we search for new sources by measuring fluxes for source positions covering the LIGO arc or for the neutrino detection position. This is a search for extended (time) emission.
- We performed these searches for GW150914 (Connaughton et al 2016), GW151226, and LVT151012 (Racusin et al. 2016) using ± 1 day, 1 month, and 1 year if data were available.
- We have performed similar searches for neutrinos
- To date we have not detected any new sources in these searches

Summary

- GBM detects a broad range of transients, on timescales from milliseconds (TGFs) to years (X-ray binaries and Crab Nebula variations)
- GBM is especially well suited to detecting short GRBs due to its wide field of view, high duty cycle, and broad energy range.
- GBM is the most prolific detector of short GRBs available and we are eagerly awaiting detections of gravitational waves from NS-NS mergers!
- In the meantime, there is plenty of science to do with GBM data.